CLUMPY GALAXIES IN GOODS AND GEMS: MASSIVE ANALOGS OF LOCAL DWARF IRREGULARS

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ABSTRACT

Clumpy galaxies in the Galaxy Evolution from Morphology and SEDs and Great Observatories Origins Deep Survey fields are examined for clues to their evolution into modern spirals. The magnitudes of the clumps and the surface brightnesses of the interclump regions are measured and fitted to models of stellar age and mass. There is an evolutionary trend from clump clusters with no evident interclump emission to clump clusters with faint red disks, to spiral galaxies of the flocculent or grand design types. Along this sequence, the interclump surface density increases and the mass surface density contrast between the clumps and the interclump regions decreases, suggesting a gradual dispersal of clumps to form disks. Also along this sequence, the bulge-to-clump mass ratios and age ratios increase, suggesting a gradual formation of bulges. All of these morphological types occur in the same redshift range, indicating that the clump cluster morphology is not the result of bandshifting. This redshift range also includes examples of interacting galaxies with tidal tails and other characteristic features, indicating that clump clusters, which do not have these features, are not generally interacting. Comparisons to local galaxies with the same rest wavelength and spatial resolution show that clump clusters are unlike local flocculent and spiral galaxies primarily because of the high clump/interclump contrasts in the clump clusters. They bear a striking resemblance to local dwarf irregulars, however. This resemblance is consistent with a model in which the clumpy morphology comes from gravitational instabilities in gas with a high turbulent speed compared to the rotation speed and a high mass fraction compared to the stars. The morphology does not depend on galaxy mass as much as it depends on evolutionary stage: clump clusters are 100 times more massive than local dwarfs. The apparent lack of star formation in damped Lyman alpha absorbers may result from fast turbulence.

Key words: galaxies: evolution – galaxies: high-redshift – galaxies: irregular – galaxies: peculiar – galaxies: starburst

Online-only material: color figures

1. INTRODUCTION

Star-forming galaxies become increasingly irregular at higher redshift with blue clumpy structure, asymmetry, and a lack of central concentration (Glazebrook et al. 1995; Abraham et al. 1996a, 1996b; van den Bergh et al. 1996; Driver et al. 1995, 1998; Im et al. 1999). These three features are included in the CAS classification system (Conselice 2003), which has identified such irregularities in a large fraction of galaxies in deep fields (e.g., Conselice et al. 2005; Menanteau et al. 2006). Similar observations of irregular structures were obtained from color dispersions in high-redshift galaxies (Papovich et al. 2005), Gini coefficients (Lotz et al. 2006), Sersic indices (Cassata et al. 2005; Ravindranath et al. 2006), UV imaging (de Mello et al. 2006), and various combined methods (e.g., Neichel et al. 2008).

The kinematics of disks at intermediate redshifts also show irregular structures (Erb et al. 2004; Yang et al. 2008), suggesting an important contribution from unstable gas dynamics (Law et al. 2009). Turbulent motions are large compared to the rotation speed (Förster-Schreiber et al. 2006; Weiner et al. 2006; Genzel et al. 2006, 2008; Puech et al. 2007), although there can be underlying systematic rotation too (e.g., Bournaud et al. 2008).

During the last few years, we have examined the properties of clumps in high-redshift irregular galaxies, including chain galaxies (Cowie et al. 1995) and their likely face-on counterparts, the clump-clusters (Elmegreen et al. 2004), in an effort to understand star formation and to look for signs of evolution toward modern Hubble types. We have determined clump masses and ages from population synthesis models and suggested the clumps form by gravitational instabilities in a gas-rich disk (Elmegreen & Elmegreen 2005; Bournaud et al. 2007, hereafter BEE). The clumps are generally more massive than star complexes (Efremov 1995) in local galaxies, which suggests that the turbulent speed in the neutral and molecular gas is large as well, perhaps in the range of 20–50 km s$^{-1}$, considering the characteristic mass of a disk instability (and as measured in a z = 1.6 clump cluster; Bournaud et al. 2008). Gas column densities have to be large too, around 100 $M_\odot$ pc$^{-2}$ (Elmegreen et al. 2009, hereafter EEFL). These properties are reasonable considering the youthful stage of the systems we are studying. The high turbulence may come from gas accretion because it has to be in place before the clumps form in order to define the clump mass, and because the star formation feedback that generates turbulence in local galaxies is relatively ineffective when the velocity dispersion of the whole interstellar medium is large. High dispersion star-forming clouds are tightly bound and not easily disrupted by star formation pressures (Elmegreen et al. 2008). Clumps also produce high-velocity dispersions by themselves in the surrounding gas (BEE).
This interpretation of asymmetric clumpy structure as an indication of instabilities in a gas-rich disk is not the only possibility. When asymmetry and clumpiness are observed in a local L* galaxy, they are usually indicative of a merger. Faint peripheral structures such as tails and bridges contribute to this identification locally. As a result, asymmetric and clumpy structure in high-redshift galaxies has also been considered to be the result of mergers (e.g., Conselice et al. 2003; Treu et al. 2005; Lotz et al. 2008; Conselice et al. 2009, and references therein). This interpretation is reinforced by expectations from the lambda cold dark matter (ACDM) model, in which dark matter halos grow by hierarchical merging (Davis et al. 1985). For example, a recent study by Jogee et al. (2009) suggested that 16% and 45% of galaxies with stellar masses larger than $2 \times 10^{10}$ $M_\odot$ had a major or minor merger, respectively, at redshifts between 0.24 and 0.80. Jogee et al. identified these galaxies as mergers based only on their asymmetric and clumpy structure, as determined both by eye and by the CAS system. The actual fraction of galaxies that are clumpy in this redshift range is smaller than the Jogee et al. merger fractions, because they, like others, correct the observed fractions upward to compensate for the low fraction of time during which a merger morphology should be visible. López-Sanjuan et al. (2009) also used the asymmetry index for galaxies in the range $0.35 < z < 0.85$ and derived a corrected major merger fraction of 20%–35% for $M_B < -20$ galaxies.

The key assumption for these and other merger interpretations is that baryons come together in a clumpy fashion like the CDM, and star formation occurs early and efficiently in the baryonic clumps, which then merge as little galaxies rather than as smooth gaseous flows. Early numerical simulations reinforced this view, although the results of these simulations depended strongly on the recipes for thermal equilibrium and star formation, which are uncertain. Significant merging is untenable in the instability model of clump formation because then the pre-existing stars would make a spheroidal component in the remnant (e.g., Abadi et al. 2003), and this component would cause the instabilities to appear as spiral arms rather than discrete clumps (Bournaud & Elmegreen 2009).

Other aspects of galaxies expected from mergers are not generally observed. Law et al. (2007) noted that the UV morphology of a galaxy is not related to the star formation rate (SFR), which led them to conclude that the irregular structure is probably not the result of a merger. Jogee et al. (2009) also found that the SFR is not correlated with galaxy morphology. In local gas-rich mergers, even with weak tidal forces, there is usually a significant increase in the SFR compared to isolated galaxies (Larson & Tinsley 1978; see reviews in Sanders & Mirabel 1996; Kennicutt 1998).

The thermodynamics of cosmic gas is the key issue in the theoretical side of this debate. Whether the gas, which tends to follow the dark matter, cools enough to form stars in clumps before it assembles into $M^*$ galaxies, or instead enters the $M^*$ halos in smooth flows, depends on the balance between atomic collisional cooling and compressional and radiative heating. Recent simulations that treat this thermodynamics in detail now seriously question the baryonic merger scenario. Murali et al. (2002) first did cosmological simulations with enough resolution to include both large-scale flows and individual galaxies. They found that cold flows of unprocessed gas can get directly down to the $M^*$ scale without clumping into little galaxies first. They suggested that galaxy growth is dominated by smooth flows rather than mergers of pre-existing galaxies. Birnboim & Dekel (2003) confirmed in spherically symmetric collapse calculations that gas cooling can be faster than compressional heating for low-mass galaxies (see also Binney 1977; Kay et al. 2000), in which case the inflowing material does not shock to the dark matter virial temperature. Semelin & Combes (2005) found the same dominance of cold cosmological inflow to a disk, and noted that the final accretion tends to align to the disk plane. Dekel & Birnboim (2006) subsequently studied the stability of halo shocks and showed simulations where cold gas streams penetrated the hot halos. They found that the maximum halo mass for the cold flows is comparable to the mass dividing blue and red galaxies in the local universe and suggested that the difference between these two types of galaxies is the result of a difference in the gas accretion mode. Massive dark matter potentials shock their accreted gas to a high temperature, which slows or prevents in situ star formation and tips the balance of processes contributing to stellar growth in favor of mergers. More recently, Dekel et al. (2009b) showed detailed simulations and concluded that 2/3 of the inflow mass is smooth gas accretion and the rest is clumpy merger-like accretion; they concluded that most of the stars in the universe form in the disks of massive ($>10^{11}$ $M_\odot$) “stream-fed” galaxies during the redshift interval from 1.5 to 4. Dekel et al. (2009a) and Agertz et al. (2009) now find that cold flows can lead to the formation of clumpy galaxies via gravitational instabilities in the accreted disks.

Following Murali et al. (2002), the same team now led by Kereš et al. (2005) also did smoothed particle hydrodynamic (SPH) simulations in a cosmological context. They showed that accretion to low-mass galaxies (baryonic mass $<10^{10.3}$ $M_\odot$; halo mass $<10^{11.4}$ $M_\odot$) along cosmological filaments remains cold and gets all the way to the central disk, while high-mass galaxies shock-heat the accreting gas before it cools. They suggested that because of this mass dependence, the cold mode dominates all galaxies at high redshift and is most important for low-density galaxies at low redshift. Recently, Kereš et al. (2009) confirmed these results in a larger simulation and suggested that cold flows dominate the SFR at all redshifts. In another study, Ocvirk et al. (2008) included the effects of metallicity. They derived the same threshold mass for virial shocks as the other groups but suggested that the threshold mass for cold flow penetration of hot halos increases with redshift as a result of changes in the metal-dominated cooling rate. At higher resolution, Brooks et al. (2009) were able to study the time development of a galaxy disk subject to shocked and unshocked inflows and to mergers of smaller galaxies in a cosmological context. They found that unshocked gas builds the disk much faster than shocked gas, which eventually accretes slowly and for long times after cooling. In their model for a galaxy the size of the Milky Way, the fraction of the disk stars coming from merged galaxies is small, ~25%.

The distinction between clumpy disk structure that results from gravitational instabilities in a highly turbulent interstellar medium and clumpy disk structure that results from the merger of two or more galaxies should be evident at moderate-to-low redshifts in the Great Observatories Origins Deep Survey (GOODS; Giavalisco et al. 2004) and Galaxy Evolution from Morphology and SEDs (GEMS; Rix et al. 2004) fields. These surveys have exposure times that highlight the $z < 1$ universe and are large enough to contain the relevant types as well as rare intermediate cases. Galaxies with asymmetric clumps, galaxies with double cores and tidal features (Elmegreen et al. 2007b), and galaxies with smooth spiral arms, are all present in
GEMS and GOODS over the same redshift range. This mixture minimizes the bias from bandshifting and surface brightness dimming.

With this in mind, we searched GEMS and GOODS for clump clusters, chain galaxies, and spiral galaxies. For the clump clusters and face-on spirals, we measured the magnitudes of star-forming clumps and their adjacent interclump regions in the available Advanced Camera for Surveys (ACS) passbands. For the chains and edge-on spirals, we measured the thicknesses of the disks. There is generally an evolution toward smaller clumps and smoother disks at lower redshifts. The relative number of combined clump clusters and chains found in GOODS and GEMS is only ~10% compared to spiral galaxies, while it is ~50% in the Ultra Deep Field (UDF; Beekwitt et al. 2006) out to $z \sim 4$ (Elmegreen et al. 2005). We also found evidence for a progression in relative clump mass, surface density, and age along the morphological sequence from clumpy systems with no visible interclump stars, to clumpy systems with red underlying disks, to spirals with relatively smooth disks. This is the same evolutionary trend found in the UDF for more distant galaxies (EEFL). The trend seems to illustrate how modern disks and bulges form from the evolution, migration, and dispersal of star-forming clumps.

The motivation in other studies to interpret high-redshift clumpy asymmetric galaxies as merger remnants stems primarily from the analogous morphology of local merger remnants, as discussed above. However, there is another type of local galaxy with this morphology that is not a merger remnant, the dwarf irregular. We consider in Sections 5 and 6.3 the possibility that the internal structure of high-redshift clumpy galaxies is a scaled-up version of that in local dwarf irregulars. The local dwarfs get their clumpy structure from large values of two dimensionless quantities: the relative gas fraction in the disk and the relative length scale for disk gravitational instabilities. The large unstable length compared to the disk radius follows from another dimensionless quantity, the ratio of the gas turbulent speed to the galaxy rotation speed. In the case of dwarf irregulars, the large value for this speed ratio is the result of a low rotation speed (50–100 km s$^{-1}$) combined with a normal turbulent speed ($\sim$10 km s$^{-1}$). If high-redshift galaxies have an equally large ratio, then it would arise from a high turbulent speed at the normal rotation speed in an $M^*$ galaxy.

The disk instability model for clump formation also requires the gas accretion rate to be larger than the SFR for at least an orbit time. Otherwise, star formation would reduce the gas density and make the layer more stable. Such high temporary rates could be the result of irregular inflows, where the gas and dark matter enter a galaxy in separate bursts. Clumpy disks form or reform after the most recent gas accretion event. Such a dependence between morphology and accretion history may explain why clumpy disks exist over a wide range of redshifts (Elmegreen et al. 2007a); i.e., clumpy structure at late times could be initiated by a recent gas accretion event. Murali et al. (2002) also consider late-time galaxy formation by recent cold flows. Evidence for late-stage galaxy formation was presented by Noeske et al. (2007), based on the SFR versus mass for different redshifts.

In what follows, the data used for the analysis of GOODS images are described in Section 2, the clump masses, surface densities, ages, and SFRs are discussed in Section 3, and the disk thicknesses are in Section 4. Section 5 makes a comparison between two clumpy, high-redshift galaxies and a local flocculent galaxy observed with the same rest wavelength and convolved to the same spatial resolution, and another similar comparison between a high-redshift galaxy and a local dwarf irregular. The local flocculent is clearly different from clump cluster galaxies in terms of the clump-to-interclump mass contrast and brightness contrast, but the local dwarf irregular is indistinguishable except for a factor of $\sim$30 in mass. A discussion of the implications of our study is in Section 6: Section 6.1 reviews clump origins and trends with redshift, Section 6.2 considers clump coalescence to make a bulge, Section 6.3 explores further the analogy with local dwarf irregulars, and Section 6.4 offers a solution to the lack of star formation in damped Lyman alpha absorbers. The conclusions are in Section 7.

2. DATA, MORPHOLOGY, AND GENERAL IMPLICATIONS OF THE MORPHOLOGY

The GOODS survey comprises images of 18 ACS fields surrounding the UDF in four passbands, $B_{435}$, $V_{606}$, and $i_{775}$, and $z_{850}$ to $z \sim 1.5$. We searched all of these fields for clumpy galaxies of various types and selected ~100 for closer study. We also searched five GOODS fields for spiral galaxies and selected representative cases to cover the same redshift range as the clumpy galaxies. Examination of the clump cluster images suggested that some were questionable as individual galaxies: some could be foreground–background pairs and others could be interacting galaxies with tidal features. These were rejected from the current study. Galaxies that were too highly inclined to measure or distinguish the clumps were also rejected. This left a sample of 93 galaxies: 26 spirals with clear spiral arms and bulges; 35 flocculent spirals with central red bulges; 15 clump clusters without central red bulges but with an underlying red disk; and 17 clump clusters with neither central red bulges nor obvious underlying disks. Disk vertical scale heights were measured in an additional 62 chains and edge-on spirals from GOODS.

The GEMS survey consists of 63 fields surrounding the GOODS fields to slightly shallower depths ($z \sim 1.2$) in two passbands ($V_{606}$ and $z_{850}$). We selected a sample of 166 edge-on spirals and chain galaxies larger than 10 pixels in diameter and measured their perpendicular scale heights. We also selected a sample of 213 clump clusters and measured 810 star-forming clumps. Because the accuracy of the population synthesis fits is lower with only two passbands in GEMS, their measurements were done as a check on the more detailed GOODS measurements.

Figure 1 shows four morphologies of GOODS galaxies that are useful for consideration here. On the left are two spiral galaxies that are somewhat normal-looking compared to modern spirals. Next are two galaxies with clumpy star formation and small red bulges. They resemble local flocculent galaxies but have larger and fewer clumps than the local analogs (see Section 5). The galaxies in the third image from the left have clumpy star formation without an obvious bulge, but there is still a red underlying disk in each. The two on the right are clumpy without any obvious underlying disk. These four galaxy types extend our previous classifications to more modern systems. In Elmegreen et al. (2005), we classified disk galaxies in the UDF as either spirals or clump clusters, considering that a third class, chain galaxies, represents an edge-on version of the clump clusters. All but the leftmost pair in Figure 1 would have been called clump clusters according to that classification, especially in the UDF where the bulges in the second-from-
the left galaxies would most likely have been missed because of band shifting and faintness. The presence of bulges in some clump clusters was recognized in EEFL using NICMOS images of the UDF. The three pairs on the right in Figure 1 have classifications like galaxies in that EEFL paper: clump clusters with bulge-like clumps, clump clusters with red disks and no bulge-like clumps, and clump clusters without any evident red component. The first of these, the flocculent class, has not been distinguished in our high-redshift surveys before. These are evidently normal disks that have weak or no stellar density component. The first of these, the flocculent class, has not been distinguished in our high-redshift surveys before. These are evidently normal disks that have weak or no stellar density waves, like local galaxies with the same appearance.

Figures 2–5 show more examples of each morphology, presented in the order of increasing COMBO17 spectrophotometric redshift (Wolf et al. 2008). The presence of each type over a wide range of redshifts suggests that clump clusters are not bandshifted spiral galaxies. A similar redshift comparison was made for six morphological classes in the UDF (Elmegreen et al. 2007a). If the clumpy phase is short-lived, as simulations suggest, then either galaxy formation is prolonged so that clumpy galaxies appear even as late as \( z \sim 0.1 \), or clump morphology is transient, possibly following a significant event of gas accretion late in the galaxy’s life.

3. CLUMP PROPERTIES

3.1. Method of Analysis

The magnitudes of 373 clumps were measured in four passbands for all of the 93 selected galaxies in GOODS. Measurement was done using the program imstat in the Image Reduction and Analysis Facility (IRAF\(^5\)) with the same field position and size for each passband (see discussion in EEFL). Clump boundaries were typically \( \sim 10 \sigma \) above the noise and measurement errors \( \sim 0.1 \) mag. Boxes were used to define magnitudes because the clumps are pixelated; a typical clump diameter is 3–5 pixels with a box shape close to square. Clump color is much less variable than the clump magnitude. Slight shifts in selecting the boundaries of these fields would yield \( \sim 0.05 \) mag deviations in the colors. The brightest clumps were considered to be bulge-like clumps in clump cluster galaxies without obvious red bulges (unlike in EEFL where only the red clumps were considered to bulge-like).

We measured the surface brightnesses of detectable interclump regions that are adjacent to the clumps. This was done using the IRAF task pvector, which takes a pixel-wide intensity cut through the galaxy, and it was also done using selected rectangular regions with the IRAF task imstat. Contours made with the IRAF task contour provided further checks on the interclump brightness. The choice of which interclump region to measure is subjective. We picked regions fairly close to the clumps in most cases, and used the same interclump measurements for several clumps if there were limited options. Clump clusters are extremely clumpy and the surface brightness in the interclump region varies a lot, from something that might be representative of a clump pedestal to something too faint to detect at all. Because we only measured regions considerably above the background noise, there is a lower limit to the intrinsic interclump surface brightness that increases as \( (1 + z)^3 \), which is the cosmological surface brightness dimming factor.

Figure 6 shows histograms of the difference between the \( I_{775} \) surface brightness at a level of \( 1 \sigma \) noise in the sky and the \( I_{775} \) surface brightness of each interclump region. Solid blue lines are for spirals and dashed red lines are for clumpy galaxies of various types. This figure indicates that the average interclump region chosen for our study is about 2 mag arcsec\(^{-2}\) above the \( 1 \sigma \) level of the sky, which is 25.2 mag arcsec\(^{-2}\) in the \( I_{775} \) band. This difference corresponds to a factor of 6.3 above the \( 1 \sigma \) noise level. The interclump surface brightness is 2–3 times more accurate than \( 6.3 \sigma \) because each measured interclump region contains 4–10 pixels. The peaked nature of the distribution illustrates the point of the previous paragraph; i.e., that most interclump measurements have about the same surface brightness above the background noise level, in which case the intrinsic interclump surface brightness, after correcting for cosmological dimming, increases about as \( (1 + z)^4 \).

The relative uncertainty per pixel in the surface brightness is approximately the inverse square root of the counts. We noted

\(^5\) IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
above that the clump boundaries are at about the 10σ level for background noise σ, which makes the average count for the clumps ~20σ, and we also showed that the interclump regions are at an average level of 6.3σ. The ratio of these two mean intensities is ~3, and the inverse square root of this is ~60%.

The flux from each star-forming region was determined by subtracting the surface brightness of the adjacent interclump region from the average surface brightness of the clump, and then multiplying the result by the area of the clump (that is, the area of the box used to determine the average surface brightness of the clump). Clump colors were determined from the differences between the background-subtracted clump magnitudes. For the purpose of understanding clump dynamics, the total clump mass, including the older stars inside the clump, should be used, but for the purpose of understanding star formation, only the excess young mass above the background should be used. Our previous studies of clumps in UDF galaxies did not subtract the background disk because it was generally very faint.

The observed colors $B_{435} - V_{606}$, $V_{606} - i_{775}$, and $i_{775} - z_{850}$ of each background-subtracted clump and each interclump region were fitted to three model parameters: age, star formation decay time in an exponentially decaying model, and extinction (see EEFL). We used the stellar evolution models of Bruzual & Charlot (2003) for the Chabrier (2003) initial mass function (IMF) and a metallicity of 0.008 (equal to 0.4 solar). Estimates of dust absorption used the wavelength dependence in Calzetti et al. (2000) with the short-wavelength modification in Leitherer et al. (2002), considering as templates six multiples ($M_A = 0.25, 0.5, 1, 2, 4,$ and $8$) of the redshift-dependent intrinsic $A_V$ in Rowan-Robinson (2003). Corrections to the model spectra were made to account for intervening hydrogen absorption, following Madau (1995). Spectrophotometric redshift measurements come from the COMBO17 survey (Wolf et al. 2003, 2008). The templates considered decay times of $\tau = 10^7, 3 \times 10^7, 10^8, 3 \times 10^8, 10^9, 3 \times 10^9,$ and $10^{10}$ years. Region ages were sampled at every time step in the Bruzual & Charlot (2003) tabulation back to the age at a maximum assumed region formation redshift equal to 10. For each template, the mass was determined from the age and the background-subtracted brightness in the $i_{775}$ band.

The best fit results for age, decay time, extinction, and mass were taken to be the $\exp(-0.5\chi^2)$-weighted average values among all solutions, where $\chi^2$ is the sum of the squares of the observed three ACS colors divided by the corresponding measurement errors. Measurement errors were determined for each clump from the total count of emission in that clump, after first scaling count rms to count value using a large number of sample clumps (there is an approximately square root relationship between the count rms and the count value).
Age and extinction are inversely correlated so each has a relatively large uncertainty, but the effects of these two uncertainties compensate for each other in the determination of mass, which is more robust. The mass errors resulting from uncertainties in metallicity and extinction are relatively small and were discussed in detail in EEFL. Here, we estimate that the derived ages are uncertain (3\(\sigma\)) to within a factor of 4 and the masses are uncertain to within a factor of 2, based on three times the rms in the log of age and mass in the model fits. Systematic uncertainties are larger and more difficult to estimate, particularly regarding the star formation history, which is not likely to be as simple as the exponential decay model assumed here.

A potential problem with fitting a number of parameters equal to the number of measurements (three in our case) is that the most insensitive parameter can vary evenly throughout the range and then the weighted average value used for the fit is the average of the range. We checked for this by plotting versus age the rest-frame \(B-V\) color over the redshift range from 0 to 0.65, which allows interpolation of the observed magnitudes over the ACS bands to give the rest-frame apparent magnitudes \(m_B\) and \(m_V\). Figure 7 shows the result, with clump fits on the left and interclump fits on the right. There is a correlation, indicating that the fitting procedure is giving a sensible age that is younger for intrinsically bluer regions. The scatter in the age is about half an order of magnitude for the bluest colors and a few tenths of an order of magnitude for the reddest colors. This half magnitude is consistent with the factor of 4 for the 3\(\sigma\) age error mentioned above. Other tests of the same fitting procedure were given in EEFL.

### 3.2. Results

#### 3.2.1. Clump Masses

Figure 8 shows the best-fit masses for the clumps versus the redshifts for galaxy types in the four divisions defined in Figure 1. The bulges or bulge-like clumps are indicated by open red squares and the clumps that are not bulge-like are indicated by blue crosses. The bulges are generally more massive than the clumps; they are much more massive than the clumps in the spiral and flocculent galaxies, while only a little more massive than the clumps in the clump clusters. This is consistent with our findings for the UDF discussed in EEFL. Beyond redshift \(z \sim 0.5\), the average logarithms of the nonbulge clump masses (in \(M_\odot\)) for spirals, flocculents, clump clusters with red disks, and clump clusters without red disks are respectively, 7.4 \(\pm\) 0.4, 7.3 \(\pm\) 0.4, 7.4 \(\pm\) 0.5, and 7.4 \(\pm\) 0.3. The average log bulge masses at \(z > 0.5\) for the same galaxy types are 8.9 \(\pm\) 0.5, 8.2 \(\pm\) 0.4, 7.9 \(\pm\) 0.6, and 7.6 \(\pm\) 0.2. Thus the bulges in spirals and flocculents are larger than the clumps by an average factor
Figure 4. Color Skywalker images are shown for clumpy galaxies in the GOODS field with red underlying disks. Their COMBO17 redshifts (lower left), ID numbers (lower right), and 2 kpc scales (upper left) are given.

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

of 16, while the bulges in the two clumpy types are larger than the clumps by an average factor of only 2.2. This is consistent with UDF galaxies, where bulges are more similar to clumps in the clumpiest galaxies than they are in the more modern morphologies (EEFL).

The right-hand side of Figure 8 shows the ratios of the clump or bulge masses to the whole-galaxy pseudoluminosities, measured as $10^{-0.4Brest}$ for rest-frame absolute magnitudes $Brest$ given in COMBO17 (Wolf et al. 2008). This ratio is convenient for scaling the clump masses to the masses of star-forming regions in local galaxies. The ratio is also useful for understanding a selection effect evident in the left-hand panels; i.e., the drop in clump mass at lower redshift. This drop is not present in the right-hand panels, indicating that the low clump masses at low redshift are the result of systematically smaller and fainter galaxies at low redshift, with essentially no change in the clump mass for a galaxy of a given brightness. The decrease in galaxy size for lower redshift is presumably the result of a smaller sampling volume in the universe.

The log of the ratio of the clump mass to the galaxy pseudoluminosity averages $-1.1 \pm 0.5$, $-0.7 \pm 0.5$, $-0.4 \pm 0.5$, and $-0.1 \pm 0.4$ for the spirals, flocculents, clump clusters with red disks, and clump clusters, respectively. For the bulges, the logs of these ratios are higher: $0.6 \pm 0.6$, $0.3 \pm 0.5$, $-0.1 \pm 0.6$, and $0.2 \pm 0.4$. These averages consider all redshifts, so the differences between the logs for the clumps and bulges in this case are slightly different than the differences for the case of mass given above (which was for $z > 0.5$). The masses in clump clusters are larger than in spirals and flocculents, relative to the galaxy luminosities, by a factor of $10^{-0.1-[-1.1-0.7]/2} = 6$. Relative bulge masses compared to relative clump masses are larger in spirals and flocculents than they are in either type of clump cluster by a factor of $\sim 11$, which is $10$ to the power of $0.5(0.6+0.3-[-1.1-0.7])-0.5(-0.1+0.2-[-0.4-0.1])$.

In a typical local galaxy with $M_B \sim -20.3$ mag, the largest regions of star formation contain $\sim 10^5 M_\odot$. In Figure 8, an average galaxy with $Brest = -20.3$ mag has a clump mass of 10, 26, 52, and 105 million solar masses for the four galaxy types. These are $\sim 100$ to $\sim 1000$ times larger than the largest star-forming regions in local galaxies, and larger still if we consider that the same galaxies in GOODS would be fainter today because of stellar evolution. Locally, the value of log $(M/10^{-0.4Brest})$ is $-3.1$ if $M = 10^5 M_\odot$ and $M_B = -20.3$, much lower than the plotted values in Figure 8.

Some clumps in GOODS galaxies are 10 or more times larger than these average values, considering the upper range of the points in Figure 8. The maximum (non-bulge-like) clump masses reach log $(M/10^{-0.4Brest}) \sim 1$. At this value, a
Figure 5. Color Skywalker images are shown for clump clusters in the GOODS field. Their COMBO17 redshifts (lower left), ID numbers (lower right), and 2 kpc scales (upper left) are given. Their appearance is dominated by blue clumps, with no evidence for a red underlying disk. Some could be mergers; others are probably in situ disk star formation.

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

Figure 6. Histograms of the differences between the surface brightness equivalent to 1σ sky noise and the surface brightness of each interclump region. Interclump regions were chosen close to the clumps. The typical interclump region is about 2 mag arcsec$^{-2}$ above the sky noise. The value at −1.25 mag arcsec$^{-2}$ corresponds to a region near a clump where the image count was negative, meaning it was fainter than the average sky value.

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

Figure 7. As a check on the model fits, we show the expected correlation between rest-frame color and clump age (on the left) and interclump age (on the right). The ages are in Gyr. The fitting procedure is giving a sensible age that is younger for intrinsically bluer regions.

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

$M_B = -20.3$ mag galaxy would have a clump mass of $10^9 M_\odot$. The trend toward higher clump mass with redshift continues in the UDF. This trend contains a selection effect determined by the observable limits of surface brightness and physical size. An important question is whether the clumps define a physical scale, like a Jeans length, or a blending scale at the limit of
resolution in a distribution of smaller clumps. We return to this question in Section 6.1. Most likely, both effects are present: the clumps probably contain unresolved substructure, but the spacings between most giant clumps are resolved well enough to determine the clump luminosities and masses.

Figure 9 shows masses and mass-to-light ratios for 810 clumps in 213 clump cluster galaxies in the GEMS fields. These masses were estimated from the $V_{606}$ and $z_{850}$ filters used for GEMS in the manner described by Elmegreen et al. (2007b). This method makes the same assumptions as in the rest of the current paper, and uses the same Bruzual & Charlot (2003) models with exponentially decaying SFRs. The method works because for any given redshift, all of the ages and decay times in the models give about the same track on a plot of clump apparent magnitude $V_{606}$ versus color $V_{606} - z_{850}$ per unit stellar mass. These tracks differ for each redshift, so we assign each galaxy to a redshift interval of $\Delta z = \pm 0.125$, where the tracks are determined. Given the clump color on the abscissa of the plot, the deviation between the clump apparent magnitude and the track apparent magnitude is proportional to the log of the clump mass. To find the best case, we take the average in the log of clump mass from all of the different tracks, which in fact have only small differences between them (see Figures 10 and 11 in Elmegreen et al. 2007b). The error in the mass is estimated to be a factor of $\sim 3$ from the relative deviations between the tracks. For the GEMS clump masses, we do not subtract the underlying disk light in the $V_{606}$ and $z_{850}$ filters, as we do for the GOODS masses. As a result, the GEMS masses tend to be larger than the GOODS masses because the clump colors are slightly redder and the clump fluxes are slightly larger without background subtraction.

Figure 9 shows that in GEMS also, the clump masses increase with redshift yet have a nearly constant ratio of mass to total galaxy light. The average quantity $\log \left( \frac{M}{10^{-0.4B_{rest}}} \right)$ for GEMS clumps equals $0.24 \pm 0.53$, which is larger than the equivalent quantity for GOODS clump cluster clumps.
Figure 9. Clump mass (left) and ratio of clump mass to total galaxy light (right) vs. redshift for clumps in the GEMS survey that could be measured in $V_{606}$ and $z_{850}$ passbands. Background light from the interclump region is not subtracted from the clump light in this case, so these masses are larger than the pure star formation masses plotted in the previous figure. The decrease in clump mass for small redshift, combined with the constant clump mass per unit galaxy light, indicate that the galaxies are suffering a selection effect based on angular resolution and surface brightness, but the clumps inside the galaxies are not.

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

Figure 10. Redshift distribution of the excess surface density of each clump (left) and the surface density of each interclump region (right), both in $M_\odot \text{pc}^{-2}$. The red squares are for bulges or bulge-like clumps, the blue crosses are for nonbulge clumps (for an interclump region, this distinction is based on whether the region was used to subtract the background for a bulge or a clump; overlap of a cross and a square on the right means that an interclump region was used for both). Bulges have higher surface densities than clumps by a factor of $\sim 7$ for spirals and flocculents, and about the same surface densities as clumps for clump clusters. The curves plot $\log(1 + z)^4$, which is proportional to the log of the detection limit. The bulges in spirals and flocculents have higher surface densities than the bulges in clump clusters by a factor of $\sim 6$. On the right, the interclump surface density is a factor of $\sim 3$ times higher for spirals, flocculents, and clump clusters with red disks than for clump clusters without red disks. This excess is consistent with the conversion of clump clusters into spiral galaxies over time.

(A color version of this figure is available in the online journal.)
that the background is not subtracted for GEMS clumps.

3.2.2. Clump Surface Densities

The surface density of each clump was determined from its mass and size. The size is the area of the region used to measure the clump flux and is usually comparable to the size of the brightest part of the clump. Because of angular resolution limits, each clump is likely to have substructure where the surface density is larger than what we derive here. Each clump has a nearby interclump region assigned to it, but some clumps share the same region. The surface density of each interclump region was determined from its color and surface brightness assuming the usual conversions between size and magnitude for a $\Lambda$CDM cosmology (Carroll et al. 1992; Spergel et al. 2003). Each fit to the interclump surface density included the mass, age, exponential decay time, and extinction, as for the clump fits.

The left-hand side of Figure 10 shows the redshift distribution of the excess surface density of each clump, written as the total in each clump area minus the interclump surface density. The units are $M_\odot$ pc$^{-2}$. Bulges have higher surface densities than clumps by a factor of $10^{2}$ for spirals and flocculents, but the two are about the same for clump clusters. The right-hand part of the figure shows the interclump surface density for the bulge and clump regions (symbols as before). Both the clump and interclump surface densities increase with redshift as $(1 + z)^4$, which is the blue curve, because of a detection limit: we can only measure detectable surface densities (see Figure 6 and Section 3.1) and these tend to be a constant value above the sky noise.

The average vertical deviations between the points in Figure 10 and the log$(1 + z)^4$ curves are a measure of the relative surface densities for the four galaxy types. This quantity may be written as $(\log([\Sigma_{\text{clump}} - \Sigma_{\text{interclump}}] / [1 + z]^4))$. For nonbulge clumps in spirals, flocculents, clump clusters with red disks, and clump clusters, the average values of this quantity are $0.7 \pm 0.4$, $0.4 \pm 0.4$, $0.6 \pm 0.4$, and $0.7 \pm 0.4$. For the bulges, it is $1.7 \pm 0.4$, $1.1 \pm 0.5$, $0.6 \pm 0.6$, and $0.7 \pm 0.4$, respectively. Again we see that the excess surface densities are higher for bulges than clumps, and they are higher yet for the spiral bulges and flocculent bulges (average factor of $7$) than for the clump cluster bulges (average factor of $1$). This latter result implies that if clump clusters evolve into spirals, then the bulges in clump clusters have to get denser with time (by an average factor of $6$, which is $10$ to the power $0.5[1.7 + 1.1 - 0.6 - 0.7]$).

Similarly for the interclump regions, the averages of log$([\Sigma_{\text{interclump}}] / [1 + z]^4)$ for the four galaxy types are $0.9 \pm 0.5$, $0.7 \pm 0.5$, $0.8 \pm 0.7$, and $0.3 \pm 0.6$, respectively. Evidently, the interclump surface density is a factor of $\sim 3$ higher for spirals, flocculents, and clump clusters with red disks than for clump clusters without red disks. This excess is consistent with the conversion of clump cluster galaxies into spiral galaxies as some fraction of the clump mass disperses into the interclump medium.

Figure 11 shows the results again for the GOODS clump clusters, but now including several higher redshift UDF galaxies of the same morphological type. The UDF galaxies are from Elmegreen & Elmegreen (2005), with photometric redshifts from Elmegreen et al. (2007a) and analyzed in the same way as the GOODS galaxies. The minimum detectable surface density continues to increase as $(1 + z)^4$ because of the brightness detection limit. For the interclump regions, the UDF points are slightly below the curve while the GOODS points are slightly above, reflecting the longer exposure time for the UDF.

The increase of intrinsic surface density with redshift is opposite to the trend expected. Surface density should decrease with increasing redshift as younger versions of galaxies are observed. Observations of higher surface densities imply that we are seeing only the brightest parts of the disks. At higher redshifts, these parts should come more and more from the inner regions of the galaxies. Thus, the trend of increasing surface density should correspond to a trend of decreasing observable galaxy size. Many studies have shown that galaxies appear to be physically smaller at $z > 1$ because we are observing primarily the brighter inner regions of their disks (e.g., Buitrago et al. 2008; Azzollini et al. 2009 and references therein).

Figure 12 shows histograms of the ratio of the clump star formation surface density to the interclump surface density. Each count in the histogram is one clump. There is a wide range in ratios, but generally the clump clusters have higher ratios than the spirals and flocculents. For clump clusters, the typical star formation region has a mass surface density that is a factor of $\sim 2$ larger than the interclump surface density. This is considered to be a lower limit to the true clump contrast for two reasons: (1) the measured interclump surface density is always just above the sky noise (see Figure 6) and therefore higher than the minimum interclump surface density in the disk, which is probably unobservable; and (2) the clumps are barely resolved and probably contain substructure or peaks with higher surface density.
Spiral Bulges

the clumps, by factors of \(\sim\) consistent with their having comparable masses, shown above.

about the same surface density contrast as the clumps, which is contrast is much higher contrasts than the clumps.

while spiral and flocculent bulges have perturbations in the clump clusters. Clump–cluster bulges have about the same surface density contrasts as the clumps, while spiral and flocculent bulges have much higher contrasts than the clumps.

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

densities. For spirals and flocculents, the clump/interclump contrast is \(\sim 0.3\) with a wide range. Clump–cluster bulges have about the same surface density contrast as the clumps, which is consistent with their having comparable masses, shown above. Spiral and flocculent bulges have much higher contrasts than the clumps, by factors of \(\sim 3\) to \(\sim 30\).

A contrast of \(\sim 2\) between the surface density of the star formation part of a clump and the surface density of the nearby interclump region implies that the total clump/interclump surface density contrast, which means the star formation plus the background in the clump, compared to the background alone, is a factor of \(2 + 1 = 3\). Evidently, the star-forming clumps are significant gravitational perturbations in the disks of clump clusters. This contrast is much larger than in local galaxies. In the Milky Way, the average mass column density of a molecular cloud is \(\sim 170 \, M_\odot \, \text{pc}^{-2}\) (Solomon et al. 1987), which is comparable to the stellar mass column density in the inner regions of the disk. The star formation efficiency in such a cloud is only a few percent, so the surface density of an OB association or star complex is only a few percent of the background. As a result, it takes \(\sim 100\) events of star formation in local molecular clouds to significantly increase the surface density of a local stellar disk. However, in clump clusters, a single event of star formation will significantly increase the disk stellar surface density. For the clumps to be so dense, the associated gas column density in the disk must be comparable to or larger than the stellar surface density. Such high gas mass fractions were also derived from the conditions required to make the clumps by gravitational instabilities in the disk (BEE).

3.2.3. Clump Ages

Figure 13 shows the ages in Gyr of the excess emission from each clump (blue cross) and bulge (red square) versus redshift in the left-hand panels, and the ages of the associated interclump regions in the right-hand panels. The scatter in age is larger than the uncertainty in each fit, which is a factor of \(\sim 4\) (Section 3.1). This scatter is a result of continuous star formation in these disks, so some regions are intrinsically younger than others.

Bulge ages are significantly older than clump ages for spirals and flocculents, but about the same as clump ages for clump clusters. This is consistent with our findings in EEFL. There is a slight trend toward decreasing clump age with increasing redshift. We found this trend in the UDF also (EEFL). In that previous paper, where the galaxies spanned a wide range in redshifts, the age trend paralleled the age of the local universe and so was partly a result of a real physical effect, namely, that clumps and bulges in a young universe have to be young themselves. In the present study, with a smaller redshift range, this effect is expected to be smaller. There could also be some selection effect involved because higher redshifts highlight bluer regions in the disk, and bluer regions are younger.

Figure 14 shows histograms of the logarithm of the ratio of the age of the excess emission from each clump (indicated by the subscript “clump–interclump”) to the age of the associated interclump region. The histograms scatter around a ratio of \(\sim 1\) (log \(\sim 0\)) for clump clusters with no red underlying disks (bottom of the figure), and \(\sim 0.3\) (log \(\sim 0.5\)) for clump clusters with underlying red disks, spirals, and flocculents.

The age and surface brightness trends suggest an evolution from clump clusters without red underlying disks to clump clusters with red underlying disks, presumably as the clumps dissolve, age, and mix into the disks. The trend continues to the spirals and flocculents.

3.2.4. Clump Star Formation Rates

Figure 15 shows average clump SFRs determined from the ratio of each clump mass (above the background) to its age (in \(M_\odot \, \text{yr}^{-1}\)). The rates increase sharply with redshift because of a combination of two selection effects: clump masses increase with the galaxy detection limits, and clump ages decrease because of an increasing bias toward the youngest components of a clump at decreasing rest wavelength. The increase in clump mass with redshift is probably from a combination of effects: increased clump blending as the physical resolution gets worse, an increased Jeans length as the turbulent speed increases, an increase in absolute clump surface brightness at the detection threshold, and an increase in average galaxy luminosity with increasing cosmological volume. While blending must be important for some considerations, blending does not drive the increasing clump mass beyond \(z \sim 1.6\) (e.g., EEFL) because the physical resolution begins to improve. Also for \(z < 1\),
Figure 13. Ages in Gyr of the excess emission from each clump (blue cross) and bulge (red square) vs. redshift (left) and ages of the interclump regions (right). Bulges are $\sim 10$× older than clumps in spirals and flocculents, but about the same age as clumps in clump clusters.

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

blending does not cause the distinction between clump clusters and spiral galaxies because both occur at the same redshift (Figures 2–5).

Generally the clumps we measure are well separated so they are resolved from each other. They also have a high contrast to the interclump medium so we are not selecting marginally resolved local peaks in a slowly varying background. The fact that the ratio of the clump mass to the total galaxy light is independent of redshift indicates that we are not progressively smoothing over bigger and bigger subregions within a galaxy as the spatial resolution worsens. More likely, most of the clumps are identified correctly as discrete objects, and their masses are measured correctly without severe blending effects, but the whole galaxies are suffering a selection problem related to angular resolution and surface brightness limitations. That is, we choose to examine only galaxies that we resolve spatially (we limit our survey to galaxies larger than 10 pixels in diameter) and that we see above the sky noise surface brightness limit. These galaxy luminosities increase with redshift by this selection effect (see Figure 9 in EEFL), but for each galaxy, the large clumps are distinct and the clump masses are not themselves suffering an additional selection effect.

Fits to the redshift dependence of the SFR as $\propto (1 + z)^\alpha$ are shown in Figure 15, with blue curves for the clumps and red curves for the bulges or bulge-like clumps. The average of all of the slopes $\alpha$ gives SFR $\propto (1 + z)^8$. This sharp increase with redshift is the result of an increase in clump mass and a decrease in clump age, both of which vary by 1 or 2 orders of magnitude over the redshift range from 0 to 1. The relation makes sense if we consider that the clump mass scales with the galaxy luminosity (Figure 8) and the galaxy luminosity scales with the limiting surface brightness multiplied by the limiting resolved physical area, which is approximately a scaling of $\propto (1 + z)^4 \times z^2$ for small redshifts. The clump age should scale with the characteristic age of a star at the central rest-frame wavelength for the ACS. Stellar ages scale with their surface temperatures $T$ as age $\propto T^{-4} \propto (1 + z)^{-4}$. Thus, the ratio of clump mass to age should scale with $\sim z^2(1 + z)^8$ if
an average value of unity for the product of age and dynamical rate is reasonable considering that local star formation has about this same value (Elmegreen 2007). However, another selection effect could be present: fainter star-forming regions observed with the same physical resolution limit would have lower densities and longer dynamical times. If they are older, then they are redder and even fainter in rest-frame blue passbands. Thus, we tend to see the densest and youngest regions at blue rest frames. The youngest that any physically meaningful star-forming region can be is the dynamical age, because this is how long it takes star formation to begin. Thus, a value of unity is selected in any survey of the most easily observed star-forming regions. Values larger than unity represent bound clumps.

Figure 16 shows the average clump SFR again for the clump clusters, but now with the UDF values added to extend the redshift range. The product of the age and the dynamical rate is on the right. The UDF points extend the trend seen in the previous figure, considering that the spatial resolution scale stops increasing and levels off at \( z \sim 1.6 \).

4. Disk thickness

The intrinsic thicknesses of edge-on disk galaxies in the GEMS and GOODS surveys were measured by fitting perpendicular profiles made with the IRAF routine *pvect* to Gaussian-blurred \( \text{sech}^2(z/z_0) \) functions (see Elmegreen & Elmegreen 2006). The Gaussian blur accounts for the point-spread function of the ACS. Measurements of this function for 10 stars in GOODS gave FWHM dispersions of 3.21 pixels, 3.08 pixels, 2.87 pixels, and 3.18 pixels in \( B_{775}, V_{606}, r_{775} \), and \( z_{850} \) filters, respectively. (Note a typographical error in Elmegreen & Elmegreen (2006) where we quote a Gaussian sigma for the ACS stellar images of about 3 pixel but actually mean and use a FWHM equal to this value.) At redshifts of 0.1, 0.3, and 1, a FWHM of 3 pixels corresponds to a projected distance of 160, 400, and 720 pc. At higher redshift in the UDF, the projected distance gets slightly smaller; e.g., it is 640 pc at \( z = 4 \). For chain galaxies, the perpendicular profiles were taken to be as wide in the parallel-to-disk direction as the major axes, to minimize the pixel noise. For edge-on spirals (distinguished by their bulges in the ACS images), two wide profiles were taken, one on each side of the bulge, and then averaged. All ACS passbands were measured and fit, but here we discuss only the fit to the observed \( V_{606} \)-band image. There is a slight increase in disk thickness with wavelength (see Elmegreen & Elmegreen 2006).

The top right panel of Figure 17 shows the resultant thicknesses \( z_0 \) versus the absolute rest-frame \( B \)-band magnitudes, from COMBO17 (Wolf et al. 2008). Each symbol represents a GEMS or GOODS edge-on galaxy. Spirals (plus symbols) and chains (dots) have about the same thicknesses (as in the UDF; Elmegreen & Elmegreen 2006). The other panels in Figure 17 show: local galaxies in the top left, UDF chains in the lower left, and UDF spirals in the lower right. Each panel has a solid line showing the indicated linear fit to the points in that panel, and three dashed lines showing the linear fits to the points in the other panels (color coded), for comparison. The UDF results are from our previous paper; the dots with circles represent the best cases for measurement (the linear fits include all galaxies plotted). The local scale heights were determined from a \( \text{sech}^2 \) fit to \( R \)-band images; plus symbols are from Yoachim & Dalcanton (2006), \( x \) symbols are from Barteldrees & Dettmar (1994), and open circles are from Bizyaev & Kajsin (2004).
Figure 15. Left: clump SFRs from the ratio of mass above background to age (in $M_\odot$ yr$^{-1}$), vs. the redshift. The trends are fit with power laws that have an average dependence of $\text{SFR} \propto (1+z)^8$; selection effects are discussed in the text. Right: the product of the clump age and the clump dynamical rate is approximately constant over redshift and averages about 1–10. Bulges are significantly older than clumps in units of their dynamical time for spirals and flocculents.

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

Figure 16. Average clump SFR for clump clusters is extended to higher redshifts by including several UDF galaxies measured and fit to models in the same way.

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

The left-hand panel of Figure 18 shows the scale height $z_0$ versus redshift for GEMS and GOODS spirals (plus symbols) and chain galaxies (dots) and UDF chain galaxies (crosses). The two groups have similar dependencies. There is a decrease in $z_0$ for low redshift, as there was a decrease in clump mass for low redshift in Figure 8. Both decreases arise because the galaxies in these surveys are intrinsically fainter at lower redshifts. The green curve shows the FWHM of point sources in the GOODS
Figure 17. Scale height vs. rest-frame absolute magnitude is shown for local galaxies in the top left, GEMS and GOODS spirals (plus symbols) and chains (dots) in the top right, UDF chains in the bottom left and UDF spirals in the bottom right. For the UDF, dots with circles are used for the best examples of these classes. Each panel has a linear fit indicated by a solid line with the same color as the points (and indicated by the equation), and it also has the fits from the other panels in matching colors. For $M_B \sim -20$ mag, all galaxies in these samples have about the same thickness, $\sim 1$ kpc. For GEMS, GOODS, and UDF, all measurements are in the $V_{606}$ band. Local galaxies were measured in the $R$ band by various authors.

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

According to the linear fits in Figure 17, the scale height of an $M_B = -20.3$ mag galaxy is $\sim 1.2$ kpc locally, $\sim 1.2$ kpc in GEMS and GOODS, $\sim 0.86$ kpc for UDF chains, and $\sim 1.0$ kpc for UDF spirals, with $\sim 30\%$ variations around these values. These scale heights are all about the same at this absolute magnitude. Galaxies tend to be thinner at fainter magnitudes, and local faint galaxies appear thinner than high-redshift faint galaxies by about 30%. This difference is too small to be

Figure 18. Left: scale height vs. redshift for GEMS and GOODS spirals (plus symbols) and chain galaxies (dots) and UDF chain galaxies (crosses). The decrease in $z_0$ for low redshift arises because the galaxies are intrinsically fainter at lower redshifts. The green curve shows the scale corresponding to 3 pixels, which is about the FWHM of a point source in the GOODS image. Right: the difference between the measured scale height and the average scale height at the same rest-frame $M_B$ is plotted vs. redshift; there is no obvious dependence.

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

Images, taken to be a constant 3.0 pixels. The lower envelope of the point distribution is about the FWHM, so the thinnest disks are barely resolved. The right-hand panel of Figure 18 shows the difference between the measured scale height and the scale height at the rest-frame $M_B$ of the galaxy that comes from the linear fit in Figure 17. This $M_B$-corrected scale height has no redshift dependence and is the same for GEMS, GOODS, and UDF chains.
significant considering the relatively poor angular resolution of the high-redshift disks.

Figures 17 and 18 suggest that clumpy galaxies and spiral galaxies in GEMS and GOODS have about the same thickness when viewed edge-on. This is also about the same as the thickness of galaxies in the local universe when scaled to the same absolute rest-frame blue magnitude. High-redshift galaxies should fade over time, however, and the thickness of the parts currently observed at high redshift could change as well, with disk accretion increasing the gravitational force and causing a shrinkage, and satellite accretion or stellar scattering off clouds and spiral waves stirring the disk and causing an expansion.

To estimate fading over time, we use the population evolution models in Bruzual & Charlot (2003) for a Chabrier (2003) IMF and a metallicity of 0.4 solar (as elsewhere in this paper). In their tables, the absolute B-band magnitude per unit solar mass of stars varies with age $T$ in Gyr approximately as $M_B = 4.88 + 2.37 \log(T) \text{ mag}$. Then a change in $T$ from 1 Gyr to 5 Gyr corresponds to an increase in $M_B$ by 1.66 mag; a change in $T$ from 3 Gyr to 10 Gyr increases $M_B$ by 1.24 mag. If we consider these values to be typical and take 1.5 mag of fading for this population in the rest-frame $B$ band, and if we combine this fading magnitude with the fitted relation in Figure 17, $\log z_0 = -1.312 - 0.067 M_B$, then the thickness ends up too large for its faded magnitude by $0.067 \times 1.5 = 0.10$ in the log, or a factor of 1.26 in $z_0$. This argument suggests a way in which old components of today’s disks, viewed directly in GEMS and GOODS, can end up thicker than the young components by the time they are viewed in a modern galaxy. Satellite stirring and stellar scattering in the disk would do the same thickening with age, but here we see the thicker components of the main disk before subsequent kinematical evolution. We do not believe we are seeing what is called a thick-disk component, however. That would be thicker than our observed values by a factor of 2 for a given $M_B$, considering the thick disk measurements in Yoachim & Dalcanton (2006).

To check disk thickness in another way, we measured the major and minor axes lengths from IRAF pvector scans in the $V_{606}$ band for 46 chain galaxies and clumpy edge-on spirals in GOODS that had reliable redshifts in Wolf et al. (2008). The perpendicular scans used for this were the same wide scans used to determine $z_0$; these scans are as wide as the galaxies are long. For the spirals, there are two scans, one on each side of the bulge, and the average of the two widths was used. The parallel scans are as wide as the galaxies are thick. The axes endpoints were determined at intensities equal to half of the local peak. For a minor axis, this was generally half of the total peak, but for a major axis, this was half of the peak intensity of the part at each end, even if there was a brighter part in the center. The point of this procedure is that it allows us to subtract the FWHM of a stellar image from the measured axis length in quadrature, to correct for the instrument point-spread function. We take a FWHM of 3.08 pixels from Gaussian fits to stars in the $V_{606}$ band. The average minor axis width after correction for the point-spread function is $8.1 \pm 2.3$ pixels, which is enough larger than the FWHM of a star for us to be confident that we have resolved this length. The average ratio of minor to major axis is $0.16 \pm 0.06$. The range of ratios is 0.06–0.33. There was no significant difference between the chains and the spirals in these ratios. This value of 0.16 is somewhat large compared to local edge-on, late-type spiral galaxies, where a typical minimum ratio for edge-on cases is $\sim0.1$ (from the de Vaucouleurs et al. 1991 atlas; see Figure 9 in Elmegreen et al. 2005). It is larger still compared to the flattest local galaxies (Karachentsev et al. 2000). The difference between the GOODS and local galaxies is not considered to be significant, however, given the poor resolution in GOODS and the unknown inclinations of clumpy systems.

The observed axial ratios for the outer isophotes of these edge-on galaxies are larger without the correction for instrument point-spread function. At the level of $2\sigma$ sky noise, the average axial ratio for the same galaxies is $0.270 \pm 0.078$.

In another test of disk thickness, we measured the radial exponential scale lengths, $h_R$, of most of the edge-on spirals in GEMS and GOODS that are larger than 10 pixels, which is 113 galaxies. This was done in all ACS passbands, but we discuss the $V_{606}$ measurements here. These lengths were determined from thick parallel scans using pvector as above, and fit to a Gaussian-blurred model of an exponential disk viewed edge on. The Gaussian blur corrected for the point spread function, taken to be 3.08 pixels from stellar images. The half-widths $z_0$ were also determined for these spiral galaxies by fitting to a Gaussian-blurred sech$^2(z/z_0)$ function, as above. Then we determined the ratio of the scale height to the scale length, $z_0/h_R$. The average value was $0.43 \pm 0.20$. Comparing this to the ratio for local galaxies in Figure 5 of Yoachim & Dalcanton (2006), we see that the ratio in GOODS is larger than the ratio for local spirals by a factor of 2–3. It is larger even than the ratio for local galaxies with low circular velocities (dwarf irregulars), which has the largest ratio among local types, equal to $\sim0.2$ on average. This result does not mean that the GOODS galaxies are particularly thick, however, as there should be extinction corrections from dust in the midplane. The average ratio is therefore viewed to be unreliable.

The above three paragraphs suggest that the disks in GEMS and GOODS could be slightly thicker for their magnitudes or lengths than the disks in local spirals. We are highly constrained by the available resolution of the ACS, however. We find, for example, that the physical lengths of both the minor and major axes (in kpc) increase with redshift (as on the left in Figure 18). Presumably the thinnest disks at high redshift are too faint to include in our survey.

The scale height from Figure 18 and the mass column density of the interclump medium from Figure 10 can be combined to give a velocity dispersion, $\sigma$. Using the thin disk formula, $\sigma^2 = \pi \Sigma_{\text{total}} z_0$, we get $\sigma = 20(\Sigma_{\text{total}}/30 \ M_\odot \ pc^{-2})^{1/2}(z_0/kpc)^{1/2} \ km \ s^{-1}$. This normalization value of $\Sigma_{\text{total}} = 30 \ M_\odot \ pc^{-2}$ is comparable to the stellar value $\Sigma_{\text{interclump}}$ in Figure 10. If there is a significant amount of gas, then the total column density would be larger, possibly making $\sigma \sim 30 \ km \ s^{-1}$ or more. This is comparable to the velocity dispersion of stars in the solar neighborhood.

5. A COMPARISON BETWEEN GOODS GALAXIES, A LOCAL FLOCCULENT GALAXY, AND A LOCAL DWARF IRREGULAR GALAXY

The clumpy appearance of some galaxies in this study is reminiscent of that in local flocculent galaxies. Figure 19 shows a comparison between two GOODS galaxies and the local flocculent NGC 7793, blurred to the same spatial resolution and viewed at the same rest-frame wavelength. The top left panel shows a IIA-J (3950 Å) image of NGC 7793 taken with the UK Schmidt telescope and obtained from the Digital Sky Survey at the Space Telescope Science Institute (MAST). The top right
panel shows the $B_{335}$ image of the GOODS galaxy 34443, which has a redshift of $z = 0.139$ (Wolf et al. 2008). The rest-frame wavelength for this galaxy is 4350/1.139 = 3819 Å, close to the wavelength of the NGC 7793 image to its left.

The blurring of NGC 7793 was done as follows. For $z = 0.139$ in the GOODS galaxy, 1 pixel in the ACS camera, which is 0.03, corresponds to a projected spatial size of 72.6 pc. The average FWHM of stars in the ACS image at $B_{335}$ band was measured to be 3.2 pixels, so the FWHM of point sources appears to have a size of 230 pc in the image of 34443. To make a blurred image of NGC 7793 with the same physical scale for the FWHM of a point source, we first note that the original image scale is 1/7 pixel$^{-1}$, and the average FWHM of several stars in the field is 2.05 pixels. NGC 7793 is at a distance of 3.1 Mpc (NASA/IPAC Extragalactic Database), and at this distance, the desired FWHM resolution scale of 230 pc subtends 15.5; which is 9.1 pixels. Thus, we blur the original image of NGC 7793 with the routine Gauss in IRAF using a Gaussian convolution function with a Gaussian sigma that produces a net FWHM of 9.1 pixels. Considering that the original image has a FWHM of 2.05 pixels, this means we have to blur it with an additional FWHM of $(9.1^2 - 2.05^2)^{1/2} = 8.87$ pixels. The corresponding Gaussian sigma for the blur is $8.87/(8 \ln 2) = 3.77$ pixels.

The image of NGC 7793 is further degraded to make the pixel scale and the noise level about the same as for 34443. As mentioned above, the number of pixels in a resolution FWHM for the blurred image of NGC 7793 is 9.1 pixels, and the number in 34443 is 3.2 pixels. The ratio of these is 2.8, so we re-pixelate the blurred NGC 7793 image by converting each block of 3 × 3 pixels into a single pixel using the blkavg routine in IRAF. Also, the ratio of the number of counts in the peaks of 34443 to the rms of the sky was measured to be about 10, so we subtracted sky from the blurred re-pixelated image of NGC 7793 and added noise using the IRAF routine mknoise, giving it the same ratio of peak intensity to sky rms. The result of all of these steps is an image of the local flocculent galaxy NGC 7793 that has the same rest wavelength, physical resolution, pixelation, and noise level as the GOODS galaxy 34443. Figure 19 shows the two images with about the same linear and angular scales.

The bottom two panels in Figure 19 make a similar comparison between NGC 7793 and the GOODS galaxy COMBO17 17969 at $z = 1.08$. In this case, the image on the left is the NUV (2267 Å) image of NGC 7793 from the Galaxy Evolution Explorer (GALEX) satellite (Martin et al. 2005). It has an image scale of 1.5 pixel$^{-1}$ and a FWHM measured for several point sources of ~3.38 pixels. The image on the right is the $B_{335}$ image of 17969, which has a rest-frame wavelength of 4350/2.08 = 2090 Å, close to that of the NGC 7793 image. At $z = 1.08$, 1 pixel in the ACS corresponds to 245 pc, so the FWHM of a point source in 17969 has a spatial scale of 790 pc. We want to blur the NGC 7793 image to the same physical scale. At a distance of 3.1 Mpc, 790 pc subtends an angle of 52.7, which is 35.1 pixels. The intrinsic FWHM of the GALEX image is 3.38 pixels, so we have to blur it with an additional $(35.1^2 - 3.38^2)^{1/2} = 35.0$ pixels FWHM. Converting this to a Gaussian, we get $\sigma = 14.9$ pixels for the IRAF routine Gauss. Then the physical resolution of the NGC 7793 and 17969 images are the same (790 pc). Next we re-pixelate NGC 7793 using the routine blkavg with a box size equal to the ratio of the FWHM of a point source in NGC 7793, 35.1 pixels, to the FWHM of a point source in 17969, 3.2 pixels; the closest integer to this ratio is 11. Finally, we subtract sky and add noise to the NGC 7793 image. The ratio of the intensity of a typical peak in 17969 to the rms of the sky is ~20, so we add noise to the degraded image of NGC 7793 to give this same ratio. The result is the image of NGC 7793 in the lower left of Figure 19, with the same rest wavelength, physical resolution, pixelation, noise level, and scale as the GOODS galaxy 17969.

The blurred images of NGC 7793 have blended star formation regions that are about the same diameter as the star formation regions in the GOODS galaxies. NGC 7793 has a prominent exponential disk, however, so the central region looks like a big clump. This is not the case for the clump clusters. Also, in the bottom left of Figure 19, the two biggest clumps in NGC 7793 look like projection-enhanced parts of the exponential disk because they are on the minor axis. If such disks are also present in high-redshift clumpy galaxies, then they have to be much fainter relative to the clumps than in local galaxies in order to have the high clump/interclump contrast shown in Figures 12 and 19. For GOODS galaxy COMBO17 17969 in the bottom right of Figure 19, the clumps stand out sharply from the rest of the disk in the rest-frame UV, much more than the clumps in NGC 7793 at the same NUV wavelength. Thus, a primary difference between the GOODS clump clusters and a local flocculent galaxy is the high surface density contrast of the clumps in the GOODS sample. We made the same point in Section 3.2.2. Other differences are the small number and high mass of distinct clumps in the GOODS galaxies compared with local spirals.

Figure 20 shows a comparison between a GOODS clump cluster and a local dwarf irregular, Ho II, at a distance of
3.48 Mpc (NASA/IPAC Extragalactic Database). On the left is the NUV image (2267 Å) of Ho II at full resolution, which is 1.5 pixels with a FWHM of 3.4 pixels for a point source. In the center is Ho II blurred with a Gaussian $\sigma = 13.1$ pixels so that the FWHM of a point source has a size of 780 pc. On the right is the $V_{606}$ ACS image of COMBO17 18561, which has a photometric redshift of 1.367 (Wolf et al. 2008). The rest wavelength is 6060/2.367 = 2560 Å, about the same as in the Ho II image. The FWHM of a point source is 3.08 pixels, with a 0.03 pixel. At its redshift, this FWHM corresponds to 780 pc, the same FWHM as for Ho II. Thus the GOODS image of 18561 on the right has the same resolution and rest-frame wavelength as the blurred NUV image of Ho II in the center. The two also have about the same pixel scale, relative noise level, and page scale, as discussed for Figure 19. Evidently, the degraded local dwarf irregular in Figure 20 looks qualitatively similar to a clump cluster, unlike the flocculent spiral in Figure 19.

Quantitatively, Ho II and COMBO17 18561 are very different, however. The apparent $B$ magnitude of Ho II is 11.13 (Bureau & Carignan 2002) and the distance is 3.48 Mpc, so the absolute $B$ magnitude is $-16.6$. According to Wolf et al. (2008), the rest-frame absolute $B$ magnitude of 18561 is $-20.37$, a factor of $\sim 30$ brighter. The prominent clump in the upper part of 18561 has an apparent $z_{850}$ magnitude of 25.4 without background subtraction. This passband corresponds to a rest-frame wavelength of 3600 Å, similar to the $U$ band. For the redshift of 1.367, the distance modulus is 44.96 so the absolute rest-frame $U$ magnitude of the clump is $-19.6$. The $U-B$ color of Ho II is $-0.1$ (Stewart et al. 2000) so the $U$-band magnitude of Ho II is $-16.7$. Thus, the prominent clump in 18561 is 2.9 mag, or a factor of 14, brighter than all of Ho II in the rest-frame $U$ band. The mass we derive for the star-forming part of this clump is $1.3 \times 10^8 M_\odot$ and the age we get is $\sim 3$ Myr. This is the same age as the central clump in Ho II, which contains $\sim 170$ O stars and is $\sim 100$ pc across (Stewart et al. 2000).

There have been several studies of local galaxies blurred, dimmed, and bandshifted to see what high-redshift galaxies might look like (e.g., Brinchmann et al. 1998; Burgarella et al. 2001; Smith et al. 2001; Papovich et al. 2003; Taylor-Mager et al. 2007). Burgarella et al. found that the largest change in morphology comes from viewing a galaxy in the rest-frame UV, which makes a galaxy more asymmetric and less centrally concentrated than in a visible band image. In their examples of redshifted local galaxies, however, the spiral arms are usually still visible and the star-forming regions are only slightly higher contrast than they are locally. They do not look like the clump clusters shown here in Figures 4 and 5.

Overzier et al. (2008) showed that local compact UV-luminous galaxies are similar to Lyman Break galaxies when convolved to the same spatial resolution and viewed in the same rest frame. They suggested that the Lyman break galaxies are collisional starbursts, like the local galaxies. It may be that some clump clusters are collisional starbursts too. COMBO17 28751, 39638, 26313, 44885 and perhaps others in Figure 5, have extended features that could be tidal in origin. However, if chain galaxies are the edge-on counterparts to clump clusters, then these galaxies are generally too flat to be tidally distorted in a collision (Elmegreen & Elmegreen 2006). We examined collisional galaxies in GOODS (Elmegreen et al. 2007b) and at these modest redshifts, they still look like local collisions. Also, the clump cluster UDF 6462 has extended features like some clump clusters in Figure 5, but it has a continuous rotation curve and a metallicity gradient, suggesting it is a single clumpy disk (Bournaud et al. 2008).

6. DISCUSSION

6.1. Giant Clumps: Bandshifting, Selection Effects, and Origins

The GOODS field offers a view of young galaxy morphology at redshifts $z < 1$ with selection effects caused by bandshifting, variable spatial resolution, and variable surface brightness dimming. The effects of bandshifting are not so bad at these redshifts, though. GOODS galaxies observed in the $z_{850}$ ACS band are bandshifted only to their rest-frame $V$ or $B$ band, where we know what local galaxies look like. UDF bandshifting for $z \sim 2 - 3$ galaxies is much worse, as it takes a $z_{850}$ image into the rest-frame UV, where even the local morphologies are uncertain and, in some cases, quite different than in the optical bands. Variable spatial resolution is more of a problem for GOODS than the UDF because the spatial scale per pixel increases strongly with redshift at $z < 1.6$; the increase slows and reverses beyond that. Surface brightness dimming is a problem in both near and far redshift surveys, limiting what can be seen to the brightest resolved features and producing a strong correlation between measured surface brightness and redshift. Here, we discuss several properties of young disk galaxies that are relatively insensitive to these three selection effects.

First of all, the two new morphologies found at $z \sim 2$ in the UDF, i.e., chain galaxies and clump clusters, are still present in GOODS in the redshift range from 0 to 1, alongside normal-looking spirals. This demonstrates that bandshifting alone does not cause the appearance of clumpy structure. Clumpy galaxies still have no spirals or regular exponential disks in GOODS, and about half still have no bulges. The clump/interclump contrast in total mass surface density is large for these galaxies, e.g.,
~2–5, even in the rest-frame $B$ band. It is significantly smaller, ~1.1–2, for spirals and flocculent galaxies at the same redshift in GOODS. Bulges are more massive than star-forming clumps in spirals by a factor of ~16 and older by a factor of ~10, whereas bulges are more massive than clumps in clump clusters by a factor of only 2.2 and they are not significantly older. Spirals and flocculents have higher interclump mass surface densities than clump clusters too, by a factor of ~3 at the same redshift. All of these results suggest that clumpy galaxies are younger versions of spiral and flocculent galaxies, and that this youthful appearance extends even to objects observed at recent cosmological times ($z < 0.2$).

The redshift dependencies of surface brightness, physical resolution, and rest-frame wavelength all contribute to a strong redshift dependence for the choice of galaxy in this survey, and ultimately, to the derived average SFR in a clump, given that clump mass scales with galaxy luminosity. This rate therefore has little utility in understanding the star formation process. However, our result that the age of a clump is comparable to its dynamical time, as determined by the average clump density, is relatively insensitive to these selection effects. This result confirms our assumption that the clumps are star-forming regions and it suggests that star formation is a dynamical process involving disk self-gravity.

The similarity between the star formation age and the dynamical time also makes a strong statement about the origin of the clumps: they are not separate galaxies brought in from outside and settling into a common disk. If they were, then their background-subtracted ages would be significantly larger than their dynamical times, i.e., they would be older, self-bound, and more independent of each other.

The suggested origin of disk clumps by gravitational instabilities is analogous to the process commonly thought to trigger large-scale star formation in local galaxies (e.g., Elmegreen 2002). If we take the analogy to local galaxies further, then we can compare the largest scales of star formation in the two cases. For local galaxies, the largest scale of coherent star formation is about the disk Jeans length, $L_J = \sigma^2 / (\pi G \Sigma)$, for velocity dispersion $\sigma$ and mass column density $\Sigma$ (which includes stars if the stellar and gaseous dispersions are comparable). The mass on this scale is about the Jeans mass, $M_J = \sigma^4 / (G^2 \Sigma)$. That this is a characteristic scale for star formation and not a preferentially sampled scale has been shown by power spectra of optical galaxy images (Elmegreen et al. 2003a, 2003b), fractal structure analysis of optical and H II region images (Elmegreen et al. 2006), and autocorrelation analysis of cluster positions (Zhang et al. 2001). In these studies, the structure involved with star formation itself is scale-free, i.e., it has a power-law power spectrum, but that power law only extends up to a scale of about 1 kpc, which is the characteristic or outer scale. Beyond that, star-forming regions appear somewhat independent and uncorrelated. We also note that for star formation on a dynamical time, the largest region that has a clump-like shape rather than a spiral shape, distorted by shear, is this same Jeans length (Elmegreen & Efremov 1996). This is because the dynamical time is less than the shear time on scales smaller than $L_J$ in a marginally stable disk. Thus, whether a star-forming clump is the result of interstellar condensation from a gravitational instability or the result of widespread turbulence compression in a shearing environment, there is an outer scale comparable to $L_J$.

In the context of high-redshift galaxies, there is a selection effect where we only see structures larger than the limiting spatial resolution. This structure would not generally have a characteristic length representative of the star formation process, and in fact we cannot measure such a length if the structure is unresolved. However, we have the fortunate circumstance for young galaxies that the contrast between the bright features (clumps) and the regions between the bright features (interclump stars) is very large, giving these galaxies the appearance, even in optical rest frames (Figures 4 and 5), of extreme clumpiness. Then the clump masses can be measured from their luminosities and colors even if the clumps are unresolved, without severe blending problems. To demonstrate this difference with local galaxies, we compared in Figure 19 a local flocculent galaxy with two clumpy GOODS galaxies, viewed with the same spatial resolution and rest-frame wavelength. In the local galaxy, star formation patches on the scale of $L_J$ are everywhere in an exponential disk, and their contrast is not particularly large. In the clumpy GOODS galaxy, however, there are only a few very bright regions that are well separated from each other. In this sense, they are resolvable (from each other) and measurable in mass. After subtracting the light from the surrounding disk, we found that the star-forming parts of these clumps have masses of $10^7$–$10^8 M_\odot$ in young stars, with a few clumps as massive as $10^8 M_\odot$. If there is gas in these clumps as well as stars, then the masses would be larger, perhaps by a factor of 2 or more. Because we identify this outer-scale mass with $M_J$, by analogy with local galaxies, we conclude that $M_J$ is larger for star-forming clumps in the clumpiest high-redshift galaxies than it is in spiral galaxies locally. This case is more compelling for the GOODS clump clusters than the UDF clump clusters (EEFL) because bandshifting is not as severe for the GOODS galaxies, which means that the morphological contrast to spiral galaxies is more clear.

There is still a surface brightness limit in the GOODS and UDF clump clusters that limits the clumps we can measure to only those with the highest surface densities. There should be many more fainter and smaller young regions in clump cluster galaxies than we can observe in these surveys. Thus, we know little about typical star-forming regions or luminosity functions. Our conclusion is only that the maximum mass of a coherent unit of star formation increases with redshift. If we identify this mass with $M_J$, as proposed above, then such a result would follow most sensitively from an increase in $\sigma$, the velocity dispersion of the ambient neutral medium. We have made the same point for UDF galaxies before (EEFL) and noted how observations of random gas motions tend to support this higher dispersion (Förster-Schreiber et al. 2006; Weiner et al. 2006; Genzel et al. 2006, 2008), although the dispersion in the ambient neutral medium has not yet been measured with high angular resolution.

6.2. On Clump Migration to Make a Bulge

We are interested in whether the clumps we observe are so massive and dense compared to their surrounding disks that they interact with each other and the halo, losing angular momentum and spiraling into the center (e.g., Noguchi 1999; Immeli et al. 2004a, 2004b; BEE). To study this, we estimate the ratio of clump mass to galaxy mass and compare this with the ratio in simulations where the clumps do migrate to the center. In BEE, we found that the total clump mass was $\sim 30\%$ of the disk mass ($\gas +\stars$), and the simulations formed $\sim 6$ giant clumps which moved to the center in $\sim 1$ Gyr. Thus, each clump was $\sim 5\%$ of the disk mass. For the GOODS galaxies, we use the right-hand side of Figure 8, which shows the ratio of the clump mass to a measure of the galaxy luminosity, $10^{-0.4B_{rest}}$. To convert
this luminosity to mass, we again use the population evolution models in Bruzual & Charlot (2003) for a Chabrier (2003) IMF and a metallicity of 0.4 solar. Recall from Section 4 that $M_B = 4.88 + 2.37 \log(T)$ mag per unit solar mass of stars with age $T$ in Gyr. The residual stellar mass of this population varies with age as $M = 0.60 \times 10^{-0.078 \log(T) M_{\odot}}$. If we write $M = A10^{-0.4f_{\text{gas}}}$ in analogy with the formulation in Figure 8, then we derive $A = 50 \times 10^{0.87 \log(T) M_{\odot}}$. As a consistency check, note that this gives a galaxy luminous mass $M = 2.7 \times 10^{10} M_{\odot}$ for $f_{\text{gas}} = -20.3$ mag and a mean population age of $T = 5$ Gyr.

The total galaxy mass would be large because of dark matter.

In Figure 8, $M_\text{clump} \sim 10^{-0.1 \pm 0.4} \times 10^{-0.4f_{\text{gas}}} M_{\odot}$ for clump masses $M_\text{clump}$ in clump clusters with no obvious underlying disk. The ratio of the clump mass to the galaxy mass is therefore $10^{-0.1 \pm 0.4}/A = 10^{0.8 \pm 0.4} \times -0.87 \log(T)$ for average galaxy population age $T$, in Gyr. For the average clump studied here, this mass ratio ($= 1.6\%$) is smaller than the ratio for the BEE simulations ($5\%$) by a factor of $\sim 3$ for $T = 1$. Clumps that are more massive than average by one standard deviation have a clump-to-galaxy mass ratio of $4\%$, which is close to the simulation ratio. Considering that the BEE simulations did not determine a mass limit for accretion to the center but only had clump masses that automatically came from the disk instability, the observed clumps in clump cluster galaxies could be massive enough to spiral in for some of the distance, maybe even to the center if they are also dense enough to withstand the higher tidal forces there. The clumps in the spiral and flocculent galaxies studied here are considerably lower in mass than this value for clump clusters, by another factor of 6, and are therefore not likely to spiral in significantly. The spiral clumps will probably disperse where they are, as in modern spiral and flocculent galaxies.

6.3. Clump Clusters as Massive Versions of Local Dwarf Irregulars

The comparisons in Section 5 between two local galaxies without prominent spiral density waves and GOODS clump clusters, viewed at the same spatial resolution and rest wavelength, illustrate two key differences. First, for similar size galaxies (flocculents versus clump clusters), the GOODS galaxies are more massive than average by one standard deviation have a clump-to-galaxy mass ratio of $4\%$, which is close to the simulation ratio. Considering that the BEE simulations did not determine a mass limit for accretion to the center but only had clump masses that automatically came from the disk instability, the observed clumps in clump cluster galaxies could be massive enough to spiral in for some of the distance, maybe even to the center if they are also dense enough to withstand the higher tidal forces there. The clumps in the spiral and flocculent galaxies studied here are considerably lower in mass than this value for clump clusters, by another factor of 6, and are therefore not likely to spiral in significantly. The spiral clumps will probably disperse where they are, as in modern spiral and flocculent galaxies.

A high velocity dispersion normally stabilizes a disk but clump clusters also need a high gas column density to simultaneously match the sizes and the masses of the giant clumps (EEFL). Recall that the Jeans length scales with $\sigma^2 / \Sigma$ and the Jeans mass scales with $\sigma^4 / \Sigma$, so the mass per unit length scales with $\sigma^2$. Regions that are larger by a factor of $\sim 3$ and more massive by a factor of $\sim 100$ require a dispersion that is larger by a factor of $\sim 5$ and a mass column density that is larger by a factor of $\sim 10$ (EEFL). They are unstable even with the high dispersion. The required $\Sigma \sim 100 M_{\odot}$ pc$^{-2}$ is comparable to the column density in the inner parts of modern spirals, and to determine because of selection and resolution effects, but they appear to be large compared to the radial sizes too (Section 4).

Dwarf irregulars have both a thick disk and a clumpy structure because of their large value of $\sigma/\sqrt{V}$, which results from a small rotation speed $V < 100$ km s$^{-1}$ and a normal dispersion, $\sigma \sim 10$ km s$^{-1}$. Clump clusters are apparently massive galaxies with about the same ratio of $L_j/R$ and $\sigma/\sqrt{V}$, but in this case, $V$ is probably typical of $M^\ast$ galaxies, namely, $V \sim 150$–200 km s$^{-1}$. This means that the gaseous velocity dispersion has to be high, $> 20$ km s$^{-1}$. This is not unrealistic considering observations of high velocity dispersions in the ionized gas (Section 1) and other constraints mentioned in the previous two subsections.

Another similarity between clump clusters and dwarf irregulars is that neither have prominent spiral arms. Locally, this characteristic results from a lack of strong tidal or other asymmetric forces and, in the case of dwarfs, from a large stellar velocity dispersion compared to the rotation speed. The first of these points suggests that when there are no tidal arcs the clump cluster morphology results from internal processes. This emphasizes again a likely analogy to local dwarf irregulars, rather than local mergers.

Collisions are necessary in the local universe to make a superstarburst because collisions are the only way that a local galaxy can rapidly accrete a large amount of gas. The primary ingredient for a superstarburst is rapid gas accretion—much faster than the gas consumption rate by star formation, which is only several percent of the galaxy-wide dynamical rate. Interactions can bring in gas to the inner disk of a galaxy through tidal torques and through direct contact, perhaps doubling the gas mass surface density in one dynamical time. This is much faster than the burn-off rate from normal star formation. At high redshift, however, cosmological accretion through a cold flow might double the amount of gas in a dynamical time without any other galaxy involved (Section 1). The resulting gas and starburst will generally have an irregular structure as the cold flow is not likely to be symmetric and the young disk is likely to be unstable. Thus, it is possible that a high fraction of clump cluster galaxies, and perhaps some clumpy Lyman break galaxies too, have their morphology and large SFRs because of a high gas accretion rate and a high gas turbulent speed in an intrinsically dense disk, rather than because of a current merger. This makes them high-density and high-mass analogs of local dwarf irregulars, rather than high-redshift analogs of ultraluminous infrared galaxies (ULIRGS).

Clumpy galaxies are observed in a young state, so they can have a high gas fraction and high state of turbulence. The rate of star formation is high in them because the density is high, unlike the situation in local dwarf irregulars where the intrinsic density is low and the SFR is low.

6.4. Disk Stability and Damped Lyman Alpha Limits on the Star Formation Rate

A high velocity dispersion normally stabilizes a disk but clump clusters also need a high gas column density to simultaneously match the sizes and the masses of the giant clumps (EEFL). Recall that the Jeans length scales with $\sigma^2 / \Sigma$ and the Jeans mass scales with $\sigma^4 / \Sigma$, so the mass per unit length scales with $\sigma^2$. Regions that are larger by a factor of $\sim 3$ and more massive by a factor of $\sim 100$ require a dispersion that is larger by a factor of $\sim 5$ and a mass column density that is larger by a factor of $\sim 10$ (EEFL). They are unstable even with the high dispersion. The required $\Sigma \sim 100 M_{\odot}$ pc$^{-2}$ is comparable to the column density in the inner parts of modern spirals, and...
suggests again that clump clusters are young, gas-rich versions of local galaxies.

The high dispersion suggests a solution to the problem raised by Wolfe & Chen (2006), that damped Lyman alpha absorption (DLA) in quasars often indicates a column density of H1 (N > 2x10^20 cm^-2) that is unstable in the local universe but has no associated star formation in the high-redshift universe. Wolfe and Chen noted that the observed gas has to be at least 10 times less efficient at forming stars than local galaxies, according to the Kennicutt (1998) relation. The local star formation threshold is ~5 M☉/pc^-2 (~2.6 x 10^20 H cm^-2 including He). Many DLA systems have higher column densities than this with no evident emission.

Wolfe and Chen suggested that the column density threshold could be high in DLA galaxies because at high redshift only the dense inner parts of galaxies are well formed, and these parts have high angular rotation rates (i.e., for a fixed galaxy density relative to the average density of the universe, the angular rotation rate scales approximately inversely with the universe’s age). High angular rotation rates stabilize the gas through the epicyclic frequency κ in the Toomre expression for the critical column density, \[ \Sigma_{\text{crit}} = \sigma \kappa / (3.36 G) \]. In this interpretation, stability occurs essentially because the galaxies are small. Our observations of clump clusters in the UDF do not find a size that correlates well with redshift (Elmegreen et al. 2007a), but we agree in principle with the Wolfe and Chen suggestion that the most active parts of clump clusters probably correspond to the inner regions of today’s disks, primarily because that is all we can observe at the surface brightness limit.

Wolfe and Chen also suggested that the molecular fraction could be low in DLA gas as a result of low metallicities, thereby requiring higher \( \Sigma_{\text{crit}} \) to get molecules and star formation. Local dwarf irregulars have low metallicities and molecular fractions too, but \( \Sigma_{\text{crit}} \) is lower for them than it is for spirals (Hunter et al. 1998). Other stabilizing mechanisms such as disk flaring or a lack of cold gas were ruled out by Wolfe and Chen.

The present observations suggest an additional solution to this problem. Young galaxies seem to have higher turbulent speeds than modern galaxies by a factor of ~5 or more, and \( \Sigma_{\text{crit}} \) increases in direct proportion to this speed. When star formation occurs in the unstable part of a gas-rich, highly turbulent disk, it should be fast, violent, and make massive star complexes. This is what we observe in clump clusters. For the same dispersion, regions with lower column densities should be more stable and relatively quiescent. This is apparently what Wolfe and Chen find. We suggested in Section 6.3 that the turbulent speed in the disks of young massive galaxies is ~20 km s^-1 or more. This makes them stable at column densities that would be unstable in local spirals. Measurements of DLA line widths (Wolfe & Prochaska 1998) include cases with such high values, but the overall DLA profile could be contaminated by disk rotation, making the turbulent speed uncertain.

If we consider star-forming instabilities in the context of clump cluster morphology, we can use the analogy with local dwarfs to infer that \( \sigma / V \sim (L_J / R)^{1/2} \) for velocity dispersion \( \sigma \), rotation speed \( V \), star formation scale \( L_J \), and galaxy size \( R \) (Section 6.3). Then the critical column density is \( \Sigma_{\text{crit}} \sim (L_J / R)^{1/2} (V^2 / R) / 1.7 G \) for \( \kappa \) ~ 2V/R in the case of solid body rotation (use \( \kappa = 1.4 V / R \) for a flat rotation curve). With equally clumpy morphologies, \( (L_J / R)^{1/2} \) should be the same for clump clusters and local dwarf irregulars, making \( \Sigma_{\text{crit}} \) scale with the square of the rotation speed. It should therefore be much larger in turbulent, high-redshift galaxies of normal size than it is in local dwarfs. In a galaxy with less clumpy structure, such as local spirals, \( \Sigma_{\text{crit}} \) should be smaller for the same \( V \) because \( (L_J / R)^{1/2} \) is small. Local dwarfs have the lowest \( \Sigma_{\text{crit}} \) because their lower \( V \) offsets the increase in \( (L_J / R)^{1/2} \).

7. CONCLUSIONS

Clumpy galaxies have been examined in GOODS and GEMS and their clump properties and disk thicknesses measured. We are interested in the transition between these irregular types and modern disk systems. Our results may be summarized as follows.

1. Chains and clump clusters are present at photometric redshifts down to ~0.1 or lower, along with spiral galaxies with the same magnitudes and redshifts. This observation indicates that the clumpy morphology is not the result of bandshifting. That is, chains and clump clusters are not normal spiral galaxies simply viewed in the extreme ultraviolet rest frame. There is a tendency for star formation to look more clumpy at shorter wavelengths, but the clump cluster morphology is generally more extreme than that.

2. The primary difference between clumpy galaxies and local spiral galaxies is the contrast in both intensity and mass surface density between the clumps and the interclump regions. The clump clusters studied here have contrasts in mass surface density between the young parts of the brightest clumps and the surrounding interclump regions that are factors of 1–4, which means that the total contrasts in mass surface density are factors of 2–5. Spiral and flocculent galaxies at the same redshifts as the clump clusters have much smaller clump contrasts, 0.1–1 for the young parts of the clumps, or 1.1–2 for the total.

3. There appears to be an evolutionary sequence from clump clusters with no evident red underlying disks, to clump clusters with red underlying disks and in some cases bulges, to spiral galaxies with either flocculent or long- arm spiral structures. Along this sequence, the clump/ interclump surface density contrast decreases, and bulges appear with greater distinction from the clumps in terms of mass, surface density, and age. There are no evident external processes or merger-like processes, tidal tails, etc., associated with this change in bulge and clump morphology, suggesting that bulges grow from internal disk processes. Such processes might include clump coalescence and loss of clump angular momentum, as driven by gravitational friction and asymmetrical forces (BEE).

4. This evolutionary sequence is mixed in redshift for the GOODS sample, which means that the morphologically youngest galaxies, the clump clusters with no evident interclump emission, have about the same redshift distribution as the morphologically oldest galaxies, the spirals. This mixture implies that clump clusters are either intrinsically young, and therefore form continuously from intergalactic gas over a wide range of redshifts, or clump clusters rejuvenate from faint unseen forms to the starbursting clumpy systems that we see, possibly following a major gas accretion event. Considering the resemblance between clump clusters and dwarf irregulars discussed in this paper, the faint unseen forms could be massive analogs of local, low surface brightness, dwarf irregulars.
5. There is evidence for tidal structures in some clumpy galaxies, but not in all. Generally, the clump cluster morphology is distinct from the morphology of interacting galaxies. Many other galaxies in GOODS and GEMS covering the same redshift range as clump clusters are clearly interacting, showing all the usual signs of interactions, such as tidal tails, tidal debris, and rings (Elmegreen et al. 2007b). Thus, clump clusters are not merger remnants whose tidal debris has been suppressed by cosmological surface brightness dimming. They are either somewhat isolated, or they are interacting less frequently and less strongly than conventional mergers. This, along with certain morphological details in a clumpy galaxy’s structure, suggest that galaxy growth is dominated by smooth gaseous inflow and not the merger of smaller galaxies (Bournaud & Elmegreen 2009). Recent numerical simulations of galaxy formation in a cosmological context reinforce this interpretation (Section 1). Clumpy asymmetric structure in a high-redshift galaxy does not necessarily imply a merger.

6. Clump clusters resemble local dwarf irregulars in rest-frame morphology far better than they resemble flocculent spirals and mergers. However, clump clusters have the luminosities and masses of normal spiral galaxies, which are 10 to 100 times larger than local dwarf irregulars. Thus clump clusters represent a unique galaxy stage: they are as massive as normal spirals but as irregular as dwarfs. This unique property is probably connected with their extreme youth. Although neutral gas in clump clusters is not widely observed yet, we feel confident in predicting that these galaxies will be found to have high gas fractions, as do dwarf irregulars, and high gas velocity dispersions relative to their rotation speeds, as do dwarf irregulars. The velocity dispersions of the ionized gas components are already observed to be high (Section 1).

7. Local dwarf irregulars are not a perfect analog to high-redshift clumpy galaxies. The dwarfs have low SFRs and evolve slowly, whereas the high-redshift systems are massive, star-bursting, and in extreme cases, evolve quickly to symmetric galaxies with bulges and exponential disks (BEE). The slow evolution for local dwarfs follows in part from their low disk surface density, and this helps explain why they still have high gas fractions after a Hubble time. The difference between the two cases seems to be partly a matter of scale—not an indication of different physical processes. Scaling issues have selection effects that depend on the epoch of the system and the sensitivity of the observations. At early times, massive disk galaxies take the form of clump clusters and can be as unevolved as today’s dwarf irregulars. Lower mass galaxies at these early times would not be observable. At late times, the massive clumpy disks have evolved into smooth disks, and the low-mass versions, the dwarf irregulars, are the only visible remnants of this phase.

8. The masses of star-forming regions relative to the surrounding galaxy appear to be larger by a factor of ~6 in clump clusters than in spirals at the same redshift (Section 3.2.1). The clump masses also increase with redshift, although selection and resolution effects could contribute somewhat to this mass increase. More likely, the increase in relative clump mass parallels the observed increase in relative clump separation that defines the clumpy morphology (i.e., compared to the galaxy radius), and both are the result of an increase in gas turbulent speed relative to the galaxy rotation speed. The turbulent speed of the neutral gas component in high-redshift galaxies is not yet observed, but it is predicted to be high, 20–50 km s⁻¹.

9. A high gas velocity dispersion relatively to the rotation speed increases the threshold column density for gravitational instabilities. This can explain the observed lack of star formation in gas that produces damped Lyman alpha absorption. A comparable ratio of dispersion to rotation speed in local dwarf irregulars and in high-redshift clump clusters, as suggested by their similar morphologies, also explains the low threshold column density for star formation in local dwarfs.

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