1 INTRODUCTION

Sub-mm galaxies (Smail, Ivison & Blain 1997) are candidates for the progenitors to massive spheroids in the local Universe (e.g., Lilly et al. 1999). Their luminosities ($>10^{12}L_\odot$) imply star formation rates (SFRs) large enough to build $>10^8M_{\odot}$ galaxies in much less than a Gyr, while their volume density (Barger, Cowie & Sanders 1999; Chapman et al. 2003a) is comparable to that of giant ellipticals locally. However, it is not at all clear that sub-mm galaxies do in fact build giant ellipticals. The timescales for the huge luminosities could be very short (e.g., Blain et al. 1999, Smail et al. 2003), consistent with galaxies with lower masses than the giant ellipticals. Tacconi et al. (2002) have shown evidence that local galaxies of comparable luminosities to sub-mm galaxies (Ultra-Luminous InfraRed Galaxies – ULIRGs) cannot evolve into giant ellipticals. The merger of two gas rich disks in a system of even modest mass could lead to the generation of a brief period of great luminosity (Mihos & Hernquist 1996). Sub-mm galaxy selection is susceptible to picking out the most luminous bursts at any epoch. However, detection of CO molecular gas in 5 sub-mm galaxies (Frayer et al. 1998,1999; Neri et al. 2003) and a claimed strong clustering from a spectroscopic study of the sub-mm population (Blain et al. 2004) are suggestive of massive systems for at least a fraction of the sub-mm galaxies. Locally, the most luminous objects are the ultra-luminous infrared galaxies (ULIRGs), which show evidence for being driven by mergers (Mihos & Bothun 1998).

If the sub-mm sources are snapshots of galaxies in the process of formation, their optical morphologies should reveal the mergers in process. However an ongoing difficulty with both the identification of the sub-mm galaxies (large sub-mm beam sizes and thus positional uncertainties), and the intrinsic faintness of most of the sources at optical wavelengths, has impeded a detailed morphological study of the population (Smail et al. 1998). The identification hurdle was overcome for the majority of the sub-mm population by using the deepest radio surveys (rms noise as low as 4 $\mu$Jy at 1.4 GHz – Richards 2000, Ivison et al. 2002, Fomalont et al. in preparation) to pinpoint the sub-mm emission through a high-redshift extrapolation of the far-IR/radio correlation (e.g., Helou et al. 1985, Condon 1992). The faint microJansky radio source population is dominated by star-forming galaxies and low-luminosity active galactic nuclei (AGNs), distant analogs of local luminous infrared galaxies, with suggested star-formation rates of 10-1000 $M_{\odot}/yr$ (Windhorst et al. 1995; Richards et al. 1998). The sub-mm galaxies constitute a subset of the faint radio population, with 65% of sub-mm galaxies showing radio detections to 30 $\mu$Jy at 1.4 GHz (Barger, Cowie & Richards 2000; Chapman et al. 2001a,2003b; Ivison et al. 2002).

The optical morphologies of the sub-mm galaxies have been difficult to study at high resolution, owing in part to the difficulty of obtaining deep HST images over wide areas (S$_{850\mu m}>5$mJy sub-mm galaxies number 500 deg$^{-2}$). The few sub-mm galaxies with HST observations (Smail et al. 1998, Ivison et al. 2001; Chapman et al. 2002a,b; Sato et al. 2002) show a range in morphologies, with many apparently multi-component systems suggestive of the early stage mergers, seen in ~25% of the local ULIRGs (Goldader et al. 2001, Surace & Sanders 2000). In general, local luminous galaxies appear to encompass a luminosity-dependent morphology relation, from less disturbed (Ishida & Sanders 2001) to major merger morphologies (Kim et al. 1998a,b; Goldader et al. 2001) as luminosity increases, with the most luminous ($>10^{13}L_\odot$) often dominated by QSOs (Farrah et al. 2002). However, without a statistical sample of sub-mm galaxies with HST resolution, it is difficult to assess how the sub-mm galaxies relate to local luminous galax-
ies detected with IRAS. In this paper, we present a morphological analysis of a sample of radio-identified submm galaxies using new deep HST-STIS observations in the rest-frame UV. We discuss the sample selection and observations (§ 2), analyze the submm galaxies relative to the general field population and the optically selected \( z \sim 3 \) galaxies (§ 3), and finally discuss the generally peculiar morphologies found for the submm galaxies (§ 4).

2. SAMPLE AND OBSERVATIONS

We assembled a sample of 13 submm galaxies lying in four distinct fields (the HDF, SSA13, SSA22 and Westphal-14hr) for followup with HST. The submm galaxies were detected with SCUBA on the JCMT, and pinpointed within ground-based optical images using radio, X-ray, or millimeter interferometric identifications. These submm sources were first presented in Barger et al. (1999), Barger, Cowie & Richards (2000), Chapman et al. (2000, 2001a, 2001b, 2002a, 2002c). Details of each source and its identification at multiple wavelengths are presented in Appendix 1. All submm galaxies are brighter than \( S_{\nu_{500}} > 4 \text{ mJy} \), implying far-infrared luminosities greater than \( 10^{9} \text{ L}_{\odot} \) if they lie at \( z > 1 \). Eleven out of 13 sources have associated radio emission (\( \sigma > 5 \sigma \times \text{rms} \)), with X-ray emission serving as secondary positional identifier.

These galaxy candidates were chosen from the catalogs in each field to uniformly sample the \( I \)-mag distribution of the total radio-submm galaxy population. In Fig. 1, we plot the \( I \)-mag distributions of the parent sample and the HST sample. The sources lie in the range \( I = 21-26 \text{ mag} \). We have presented measurements for \( I \)-band fluxes if the significance is \( 3 \sigma \) or higher, otherwise we have represented the non-identification of the submm/radio source by the \( 2 \sigma \) limit of the optical image. Optical magnitudes were measured using the SExtractor program (Bertin & Arnouts 1996), from our own imagery as well as imagery taken from the archives using (Westphal-14, WHT, \( I(5 \sigma) = 25.2 \) (point source limit); SSA22, CFHT-12k, \( I(5 \sigma) = 26.4 \) (point source limit); HDF, Subaru/SUPRIME – Capak et al. 2003; SSA13, KPNO/MOSAIC and Subaru/SUPRIME archival imagery \( I(5 \sigma) = 26.1 \). Ground based \( I \)-mag are measured in \( 3'' \) aperture centered on radio position. No reference was made in the selection to the ground-based optical imagery beyond the magnitude measurements, and the sample should be unbiased with respect to morphology.

HST imaging for this sample was obtained through a Cycle 10 program with the Space Telescope Imaging Spectrograph (STIS) to study the morphologies of the submm luminous galaxies. Between one and three orbits of integration time (tailored to the ground-based magnitudes), giving 2340–7280 sec of LOW SKY observation, were split between two exposures per orbit, using the 50CCD-clear filter. The pipeline-processed frames were calibrated and aligned, and cosmic ray rejected, using standard IRAF/STSDAS routines. The pixel size in the STIS images is 0.0508''c. The 50CCD-clear filter is roughly a Gaussian with 1840 Angstrom half width and a pivot wavelength of 5733 Angstrom; we refer to the associated AB magnitude as \( R' = 5733 \). The sensitivity limit reached is \( R'(5733) \sim 27.1 - 27.6 \text{ mag} (5 \sigma) \), corresponding to \( R \sim 27.6 - 28.1 \text{ mag} \) for a point source with an Sb galaxy SED. The STIS images are presented in Fig. 2, with radio centroids marked with a cross. All sources except one (SMM J131235.2) were significantly detected by STIS.

The astrometry in the small (50'') HST-STIS images was fixed by smoothing the STIS image to the ground-based I-band resolution, matching all sources \( > 5 \sigma \), and then transforming coordinate grids using the IRAF task, GEOTRAN. After maximizing the cross-correlation signal between frames, the match between \( I < 25 \) optical sources has \( \pm 0.1'' \) rms. Since the large I-band mosaic-CCD images are precisely aligned (\( \sim 0.3'' \) rms) to the radio grid (e.g., Richards et al. 1999), the HST images should be aligned to the radio frame to \( \sim 0.3'' \) rms.

While ground-based optical imaging with \( 1'' \) seeing typically identified only hints of extended sources, our STIS imaging uncovers complex morphologies and distinct components with intervening low surface-brightness (SB) emission. While only two of our sources currently have spectroscopic redshifts, there are now over 50 robust measurements of field radio-submm sources with \( < z > = 2.4 \) and an interquartile range of \( 1.8 < z < 2.8 \) (Chapman et al. 2003b; S.Chapman in preparation), suggesting that our HST targets should sample a similar redshift range. These measurements have confirmed that the submm/radio redshift indicator (Carilli & Yun 1999) has large (\( \sim 50\% \) rms) error, negating their use for studying optical luminosities. However, the angular diameter distance varies slowly over the redshift range \( z = 1-4 \), and the Carilli & Yun indicator is sufficient to assume a physical scale for their angular diameters (the submm/radio ratio indicates redshifts for our sources lying between \( z = 1.3-3.1 \) – Fig. 2). All calculations assume a flat, \( \Lambda \text{CDM} \) cosmology with \( \Omega_\Lambda = 0.7 \) and \( H_0 = 65 \text{ km s}^{-1}\text{Mpc}^{-1} \), so that 1 arcsec corresponds to 8.6 kpc at \( z = 1 \), 9.0 kpc at \( z = 2 \), 8.3 kpc at \( z = 3 \), and 7.5 kpc at \( z = 4 \).

2.1. Archival images of LBGs and NB-galaxies

In order to construct a morphological comparison sample of high redshift galaxies, we obtained HST-WFPC2 images from the Canadian Astrophysics Data Center (CADC). We concentrate on Lyman-break galaxies (LBGs – Steidel et al. 2003): rest-frame UV selected, star-forming galaxies at \( z \sim 2.5-3.5 \). We also study Ly\( \alpha \) emitters at \( z \sim 3.1 \), detected using a 80 Angstrom narrow-band filter (similar to that presented in Steidel et al. 2000), which we denote NB-galaxies.

WFPC2 images in the F814W filter were obtained for literature Lyman-break galaxy (LBG) fields with at least 3 orbits of integration. These fields include the 0000-263, 0347-383 fields presented originally in Giavalisco et al. (1996), and the SSA22 field from Steidel et al. (1998). In addition, parallel WFPC2 exposures from our own primary STIS program in the SSA22 field were used for this analysis. All NB-galaxies lie in the SSA22 field. The WFPC2 images have a pixel scale of 0.1'', and typically reach \( I = 25.5 \) at 5\( \sigma \), dependent on the precise exposure time in the particular image.

We also use morphological parameters extracted for LBGs in the Hubble Deep Field, taken in the F606W filter. Details of these measurements can be found in Conselice et al. (2003).

3. RESULTS

3.1. Submm galaxies: General morphology

We begin our analysis of the submm galaxy morphologies with a general assessment of their properties. Fig. 2 shows the radio-identified optical components to the submm sources, the photometric redshift (or spectroscopic redshift when available), and identifies the image with Table 1. The images in Fig. 2 have been smoothed with contours overlaid to increase the visibility of faint structures in the submm galaxies. For an unsmoothed version of this figure, see the companion paper...
Inspecting the images in Fig. 2 reveals that many of the submm galaxies display a distinct extended, linear morphology. A brighter knot is often asymmetrically displaced toward the end of a linear, lower surface brightness nebulosity surrounding the compact components. Multiple components are often revealed within ~1–2" scales. A few of the submm galaxies look similar to chain galaxies (Cowie, Hu & Songaila 1995), while others are suggestive of mergers in progress, a statement which we will further quantify below.

Local infrared-luminous galaxies have been identified with merging galaxy morphologies (Sanders & Mirabel 1996). As a simple, illustrative comparison, the submm galaxy component separations and elongations can be compared to the highest luminosity local galaxies: the ULIRG subset from the 1 Jy sample of IRAS galaxies from Veilleux, Kim & Sanders (2002 – see also Murphy et al. 1996). As shown in Fig. 3 the distribution in component separation of local ULIRGs is peaked at small values but has a significant tail at higher values. These measurements consider components with nuclear magnitudes of $M_B < -20.1$. The trend in Veilleux, Kim & Sanders (2002) is for the highest luminosity ULIRGs (those with $L_\nu > 3 \times 10^{12} L_\odot$) to have significantly smaller nuclear separations than the $1 \times 12 < L_\nu < 3 \times 12$ ULIRGs.

We place the submm galaxies on the same plot by measuring the maximum extent between multiple component structures, centroiding on the outermost intensity peaks within coherent structures (those exhibiting low surface-brightness bridges). The submm galaxies by contrast all have projected separations of >5 kpc, except for sources (7) and (8) which do not exhibit multiple component or extended structures. The submm galaxy STIS images likely represent rest frame wavelengths of 1500 to 3000 Angstroms, and we must be cautious of direct comparison with the $R$-band local fiducial from Veilleux, Kim & Sanders (2002). Consideration of rest frame-UV images of ULIRGs (Goldader et al. 2002) suggests that UV-bright star clusters can become apparent within galactic nuclei, but do not significantly affect the global separation measurements presented in Fig. 3.

This result is suggestive that the merger configurations of high redshift submm galaxies are typically larger and at an earlier stage than those of comparable luminosities at low redshift identified in the infrared by IRAS.

### 3.2. Submm galaxies: quantitative morphology

In order to associate quantitative measures to these visual impressions of the submm galaxies, we undertook a morphological analysis of the STIS images of submm galaxies under the LMORPHO environment (Odewahn et al. 2002). Catalogs of all sources in each of the 9 STIS fields were first prepared, covering an area 0.00161 deg$^2$. An initial SExtractor (Bertin & Arnouts 1996) catalog was assembled, computed with a $1\sigma$ threshold, a fixed 5-pixel aperture and a pre-detection smoothing Gaussian with $\sigma = 5$ pixels in a $9 \times 9$ pixel filter. A total of 619 sources were cataloged. An interactive editing tool was then used to perform star-galaxy separation and source-detection cleaning (i.e., fixing obvious mistakes in image segmentation by SExtractor or eliminating detected image defects, etc.), yielding 611 sources with photometry from the automated galaxy surface photometry package (GALPHOT). The submm sources, along with the 102 galaxies with nearby companions (< 1″), were isolated, and GALPHOT was re-run interactively to locate and eliminate nearby sources in the final photometry, and to determine more reliable local sky values to improve the photometry.

The submm optical counterparts are detected with sufficient S/N (>$10$ per beam) for detailed morphological analysis, but are clearly much too faint for application of a Fourier-based classifier (e.g., Odewahn et al. 2002). We estimate standard quantitative measures of galaxy morphology. Table 1 lists ground-based submm, radio, and I-mag photometry, along with these morphological parameters extracted from the $HST$ images: total magnitude, effective radius - $R_{50}$, concentration index, aspect ratio, image size, and mean surface brightness.

The CAS (concentration, asymmetry and clumpiness) program for morphological analysis (Conselice 2003) was also employed to quantify the asymmetries of the submm galaxies. CAS is based on the idea that structural and morphological features of galaxies are directly related to past and present underlying physical processes. The processes traced by CAS are the past and present star formation and merger activity. In the CAS system, the asymmetry index ($A$) is used to determine whether or not a galaxy is involved in a major merger (Conselice et al. 2000; Conselice 2003; Conselice et al. 2003). In this system major mergers are always found to have an asymmetry greater than some limit, which in the rest-frame optical is $A_{\text{merger}} = 0.35$. The concentration index is also a fair representation of the scale of a galaxy and is proportional to the fraction of stars in a bulge component (e.g., Graham et al. 2001; Conselice 2003).

In a similar manner to the LMORPHO analysis, galaxies with nearby companions (<1″), were isolated before calculating morphological quantities. We placed our initial guess for the center on the brightest portion of the sub-mm galaxy, and then run the CAS program to determine the asymmetry and light concentrations for these galaxies. This is done through well defined radii, centering and background removal methods which are fully described in Conselice (2003). Morphological parameters extracted include asymmetry, concentration, and a growth-curve estimate of effective radius, or Petrosian radius (Bershady, Jangren & Conselice 2000; Conselice, Bershady & Jangren 2000), and are listed in Table 2. The Petrosian radius (in units of arcsec) is defined as $1.5 \times r(\eta=0.2)$, where $\eta = 0.2$ is the radius where the surface brightness within an annulus at radius $r$ is 1/5 the surface brightness within $r$. This provides a measure of size which doesn’t depend on isophotes, complementary to that of the image moment-based $R_{50}$ from the LMORPHO analysis above. Corrections have been applied to the asymmetry and concentration values using an offset computed through the simulation how local normal galaxies would appear at the redshifts of submm galaxies (Conselice, Chapman & Windhorst 2003 – a companion paper which provides detailed CAS analysis of the submm galaxies and their merger fraction relative to other galaxy populations).

### 3.3. Comparison of the submm galaxies with the field catalog

Morphological analysis of faint sources can be susceptible to differences in the image depth, instrumental response and pixel sampling (e.g., Odewahn et al. 2002). Therefore, the most direct approach to studying the morphologies of the submm sources is to compare the photometric properties of the submm/optical counterparts with the general population of optical sources in the same 9 STIS frames. The results of this analysis are presented in Fig. 4.

Fig. 4a plots the isophotal effective radius ($R_{50}$) as a function of total magnitude. $R_{50}$ is a measure of the deprojected
radius containing 50% of the light represented by the total magnitude. Most of the submm sources (8 of 11) exhibit larger effective radii \((R_{50} > 0.35)\) per magnitude interval than the general population. In the STIS-magnitude bin 25–27 (subsuming the submm galaxies) the median \(R_{50} = 0.18\), with an interquartile range 0.12–0.23. We emphasize that while sources with \(z < 1\) cannot be compared directly with the submm galaxies, they must exhibit smaller physical scales per unit angle, making the comparison with the extended submm galaxies even more dramatic. Before attempting to interpret this result, it is important to consider how \(R_{50}\) is calculated. Each pixel is deprojected based on the isophotal ellipse shape and orientation in the usual manner, giving a measure of the pixel distance from center in the equatorial plane of the galaxy. These spatial measures are binned radially and used to compute the mean surface brightness. Integrating and extrapolating this profile produces a total magnitude and a growth curve. Using this growth curve we derive \(R_{50}\), a measure of the deprojected radius at which 50% of the total light is collected. As galaxies become more edge-on, there are fewer sampled points to use for the deprojection in the semi-major axial direction. An infinitely thin, perfectly edge-on galaxy cannot have its \(R_{50}\) calculated in this manner. As a result, galaxies approaching this idealization can exhibit \(R_{50}\) values larger than physically represented. This systematic effect, combined with the highly elongated nature of our submm galaxy images, causes the submm galaxy points in Fig. 4a to occupy the upper \(R_{50}\) envelope of the point distribution that is dominated primarily by roundish field galaxies.

The CAS estimate of the Petrosian radius provides a complementary analysis to the \(R_{50}\) result. The average Petrosian radius of the submm galaxies (2.1′), is larger than any other star-forming galaxies at low or high redshift (after taking redshift effects into account – Conselice et al. 2000). Lyman-break galaxies from the Hubble Deep Field have a Petrosian radius of 1.2′ (Conselice et al. 2003). The CAS analysis thus supports our finding using the \(R_{50}\) index, that submm galaxies are larger systems than other star-forming galaxies. We have also verified our finding from the pair separation.

Analysis of the field galaxies exhibiting a similar range of \(R_{50}\) to the submm galaxies reveals that they are split approximately in half between apparently large galaxies (likely to be nearby) and linear/edge-on galaxies. The latter are reminiscent of the submm galaxy morphologies. There are 12 field galaxies within the magnitude range \(R'(573) = 24–27\) (subsuming the magnitude range of the 8 submm galaxies with large \(R_{50}\)) having morphologies similar to those of the submm galaxies. As we have targeted our STIS images around relatively bright (>5 mJy) and rare (0.25 arcmin\(^{-2}\)) submm sources, we must scale by this value to calculate the total number of field galaxies with similar morphologies. This suggests that there are roughly 4× the number of field galaxies with similar magnitudes and morphologies to the submm galaxies, but lacking the copious bolometric luminosities (the field galaxies are not detected in the submm and radio images covering the same HST-STIS images).

Fig. 4b shows concentration index \((C32 = \text{ratio of } 75\% \text{ to } 25\% \text{ quartile sizes})\) versus magnitude. Higher \(C32\) implies a more compact light distribution (i.e., stars have large \(C32\)). We note that submm sources follow an apparently opposite trend compared to the control sample. The mean \(C32\) stays constant or increases slightly with fainter mag for the submm sources, but decreases slowly for the control galaxy sample. For the general population, we are simply seeing the effect of decreasing S/N and effective resolution as magnitudes become fainter: everything becomes diffuse (lower \(C32\)). The faint \((R'(573) > 26.5)\) submm sources have a higher \(C32\) than the control sample, suggesting submm selection picks out more concentrated galaxies.

Finally Fig. 4c shows the image size (arcsec) derived from the intensity-weighted image moment on the abscissa, and the mean surface-brightness (SB – mag per arcmin\(^2\)) within the effective radius on the ordinate. The data are discrete on the abscissa as image sizes are established in integral pixel units. The submm sources are average or fainter in mean SB per size interval than the general population. We demonstrated above that submm galaxies are more extended than the field galaxies (bigger \(R_{50}\) and Petrosian radius, and larger component separations than local infrared-luminous galaxies). The large, multi-component configurations tend to low global SB measurements. Dust extinction, expected to be significant in submm galaxies, will also make the rest-UV emission fainter. Surface brightness dimming at the high redshifts of the submm galaxies \(\propto (1+z)^4\) would also contribute to this trend.

While higher surface brightness core components are often present in the submm galaxies, the average surface brightnesses (Fig. 4c) are not unusually high compared to the field STIS population. At \(\sim 25\) mag arcsec\(^{-2}\) and redshifts with a median \(z \sim 2.4\) (Chapman et al. 2003a), they correspond to about ten times that observed in a typical spiral-disk locally.

4. COMPARISON WITH LYMAN-BREAK GALAXY MORPHOLOGIES

Lyman-break galaxies (LBGs – Steidel et al. 1996, 1999) represent rest-frame UV selected, star-forming galaxies at similar redshifts to submm galaxies (\(z \sim 2.5–3.5\)). LBGs have HST morphologies which often exhibit distorted and irregular morphologies (Giavalisco et al. 1996, Steidel et al. 1996, Erb et al. 2003). However, there has never been a chance to compare against the submm-selected galaxies. In Fig. 5, we have reproduced a complete sample of LBGs from Steidel et al. (2003) using sources from the fields presented in Giavalisco et al. (1996) and Steidel et al. (2000), as described in § 2.1, with the goal of applying the same analyses as were performed on the submm galaxies.

Another class of high redshift galaxies are the \(\text{Ly}\alpha\) emitters (e.g., Cowie & Hu 1998). These galaxies have been isolated at \(z = 3.1\) using a 80 Angstrom narrow-band filter and compared to the LBG population in the same field (Steidel et al. 2000). We have recently obtained a much larger image of the same region in a similar filter (S. Chapman, in preparation). Steidel et al. (2000) have demonstrated that only 25% of LBGs satisfy the large equivalent widths in \(\text{Ly}\alpha\) to be detectable in such narrow-band (NB) images. In Fig. 6 we show the HST images of all NB-galaxies in the SSA22 field, lying within the WFPC2 archival images. As these objects are generally much fainter than the LBGs, we have smoothed the images for visibility.

4.1. Morphological parameters

To compare the LBGs and NB-galaxies to the submm galaxies in a self-consistent manner, we applied the same morphological analysis to the complete galaxy catalogs from the WFPC2 images using the same LMORPHO environment. This enables the same normalization against the field population as we did for the STIS images of submm galaxies (§ 3.2), removing any instrumental biases. The effective radius in particular (Fig. 4a) suffers from large instrumental dependency due to the pixel scales of the images.
Fig. 4 a&b suggest that neither LBGs nor NB-galaxies generally differentiate themselves from the field galaxy population, in either effective radius or concentration index. This is opposite to the finding from § 3.2 for the submm galaxies which show larger $R_{50}$ and an opposite trend in concentration index than the field galaxies. There do appear to be several LBGs at the fainter end of the total magnitude scale which are identified as having larger effective radii. Inspection of these sources reveal them to be amongst the closest morphological matches to the submm galaxies. We emphasize that the submm galaxies and LBGs can only be compared explicitly to their respective field samples, and not to each other, due to the sensitivity of these parameters to the STIS and WFPC2 instruments.

Fig. 4c reveal the LBGs to have surface-brightnesses $\sim 1.3$ mag higher than the submm galaxies. The NB-galaxies are comparable in surface-brightness to the submm galaxies. This reflects the trend for LBGs to be dominated by a central knot of high-surface-brightness surrounded by lower surface-brightness nebulosity, as described previously in Steidel et al. (1996).

We can also study the CAS parameters of the submm galaxies compared to LBGs (here the NB-galaxies are not considered due to typically lower S/N). As discussed above, and in Conselice, Chapman & Windhorst (2003), the C,A values for the submm galaxies and LBGs have been corrected by redshifting nearby galaxies to $z = 3$ and seeing how the average C,A values change due to redshift effects. As mentioned above, the average size of the submm galaxies are larger than the LBGs: 2.1$''$ (submm) versus 1.2$''$ (LBGs). The submm galaxies also distinguish themselves from the LBGs in terms of concentration, but are similar in asymmetry. Fig. 7 plots A and C for both LBGs and submm galaxies where the submm galaxies have about the same asymmetry in the median but are more concentrated (3.2 versus 2.1 for LBGs). This difference may reflect the extended, bright starbursts or AGN in the submm galaxies.

4.2. A qualitative classification scheme

Traditional quantitative measures of morphology have difficulty contending with the range of distorted, merger configurations exhibited by the submm galaxy population. Subtle features of the morphologies can be missed by applying algorithmic processes to the inherently irregular light distributions. To complement our constraints on the quantitative morphological comparison of high redshift galaxies, we devise a simple classification scheme to encompass the range of submm galaxy morphologies, which distinguishes the main features seen in our HST images. The categories and memberships are listed in Table 3.

We delineate the following five categories: compact regular, compact irregular, elongated regular, elongated irregular, multiple component/elongated irregular. These categories were applied independently to the submm galaxies by members of our group, with the same results. The majority ($83\%$) of the submm galaxies are clearly in the latter two categories, with combinations of irregular, multiple components. Only two submm galaxies (sources 7&8) can be considered isolated and compact (compact regular category).

We attempt to place the LBGs and NB-galaxies within the same qualitative classification scheme that we applied to the submm galaxies. We have used both the unsmoothed and smoothed images to study the morphologies for consistency with the submm galaxies, and in order not to miss faint extended structures.

One difficulty with the comparison is that the LBGs are typically optically brighter than the submm galaxies, displaying high central surface-brightness cores surrounded by lower surface-brightness nebulosity (Steidel et al. 1996; Giavalisco et al. 1996; Fig. 5). The submm galaxies are generally lower surface-brightness objects, with only bright cores rising above the noise level. However, we would expect this difference to produce a one-way bias, in the sense that the submm galaxies should only appear less irregular due to loss in surface-brightness sensitivity. By contrast, the NB-galaxies are sometimes even fainter than many of the submm galaxies and even more structure may be lost in the noise.

The placement of the various LBGs into the categories outlined for the submm galaxies is often challenging, whereby very faint sources neighboring more dominant central sources are often present. While these could be classified as ‘multiple component’, they do not appear to represent the same type of major merger configuration as the submm galaxies (see also Conselice, Chapman & Windhorst 2003). We have typically classified these sources as compact irregular, when the separations of the peaks are less than 0.5$''$.

Compared with the LBGs, the submm galaxies typically appear more extended with multiple components of larger separation, although both populations exhibit similar morphologies in a few of their representatives. The NB-galaxies are more difficult to classify, but also generally appear to be more compact than the submm galaxies, although less so than the LBGs. The summary of this comparison is listed in Table 3.

5. DISCUSSION

Our HST images have identified the counterparts of submm galaxies and allowed a quantification of their morphological properties. The galaxies are characterized by larger sizes than the field population in the same STIS images, confirmed by $R_{50}$ and growth curve estimates of the radii (Petrosian radii) compared to other populations. The isophotal $R_{50}$ values provide a quantitative index which separates the peculiar morphologies of the submm galaxies from the bulk of the field population. It also appears to differentiate the submm galaxies from other high-redshift star-forming galaxies, the LBGs and NB-galaxies, which generally do not distinguish themselves from the field population in the basic morphological parameters.

However, the $R_{50}$ index does not fully describe the stunning morphologies of the submm galaxies. Many show multiple components or extended structure beyond that extracted by the analysis routines. The morphologies appear to extend over scales conceivably up to 5$''$ (~40 kpc), including regions beyond the radio emission, and therefore unlikely to be directly emitting the bulk of the bolometric luminosity. The separations of components in the submm galaxies are typically larger than comparable luminosity systems in the local Universe (Fig. 3). These morphologies are contrasted with the appearances of LBGs and NB-galaxies, which are generally more compact. The comparable large asymmetries of submm galaxies and LBGs relative to local normal galaxies indicates that LBGs are still highly irregular systems, although typically smaller.

The submm galaxies typically have implied SFRs of $\sim 1000 M_\odot$ yr$^{-1}$, and total projected areal coverage of $\sim 50$ kpc$^2$ traced in the rest-frame UV light from young stars observed by our STIS imagery (assuming the typical redshifts of the submm galaxies – Chapman et al. 2003a). This corresponds to a SFR density of $\sim 20 M_\odot$ yr$^{-1}$ kpc$^2$. Lehner & Heckman...
measurements using the MERLIN radio interferometer (This hypothesis is bolstered by the high spatial resolution radio
suggesting a dominant AGN (see also Alexander et al. 2003).

The large UV-extent of the submm galaxies may be evidence that star formation dominates the dust heating in many cases. Indeed, the only isolated source in our sample (SMM J123713.9) is also the smallest and most compact, and is in fact the brightest Chandra X-ray source from our radio-identified submm population in the HDF region, suggesting a dominant AGN (see also Alexander et al. 2003). This hypothesis is bolstered by the high spatial resolution radio measurements using the MERLIN radio interferometer (∼0.3′′ synthesized beam) of several sources from our HST sample (T. Muxlow, in preparation). In ∼50% of the cases, the radio emission is extended, and traces the UV morphology.

Can mergers truly produce a linear, elongated structure, reminiscent in some cases of chain galaxies (Cowie, Hu & Songaila 1995)? To address this question we have studied the fraction of low-redshift ULIRG merger systems which look like linear, elongated structures. As described in Conseilce, Chapman & Windhorst (2003) HST images of low-z ULIRGs are redshifted to the submm galaxy distances. 14 out of 51 (27%) ULIRGs studied in this manner have structures that look like chain galaxies. This is a comparable fraction to the submm galaxy morphologies which also look like chain galaxies. Comparing with Cowie, Hu & Songaila (1996), the fraction could be argued to be even higher. We therefore consider ∼30% to be a conservative limit of the number of low-z ULIRGs which have morphologies consistent with the submm galaxies.

The components of submm galaxies may therefore represent the first generation of merging of substantial fragments of galaxies. The large fraction of highly elongated or linear structures (some similar to the chain galaxies of Cowie, Hu & Songaila 1995) are suggestive of early stages of a dynamical event where two approximately equal mass clumps have passed by or through each other. If the components do not subsequently reach escape velocity, they will fall back into each other and become a merger in the near future. Such an initial dynamical event would induce star formation on the dynamical time scale for the system. Submm galaxies may be hosted by very high mass halos, based on their strong redshift clustering (Blain et al. 2004). This is consistent with the CO molecular gas emission line widths and possible rotation curves (Frayer et al. 1998, 1999; Genzel et al. 2002; Neri et al. 2003). If we assume only the current maximum projected separations for the submm galaxies (Fig. 3), and enclosed dynamical masses of order ∼5×10^11 M_Sun, we can use Kepler’s third law to calculate relaxation timescales. The median relaxation time is 30 Myr with an interquartile range of 31 Myr. Hydrodynamical models have shown that SNe may drive out the dust more easily than the gas in lower-mass star-forming galaxies (Mac Low & Ferrara 1998). LBGs may be longer-lived and lower-mass galaxies which expelled the bulk of their dust prior to experiencing a luminous event of the submm galaxy class.

In an accompanying paper, Conseilce, Chapman & Windhorst (2003) demonstrate that up to 80% of the submm galaxies have morphologies consistent with major mergers. However, the radio emission typically points us to a single optical source, and only in the case of SMM J141809.8 (Chapman et al. 2002a) do we have spectroscopic confirmation that three components lie at the same redshift (z = 2.99). In addition, high redshift galaxies often have complex morphologies (e.g., Cowie, Hu & Songaila 1995), and many appear qualitatively similar to the extended knotty structures shown in Fig. 2 (although we have already considered in detail the LBG and NB-galaxy morphologies, finding smaller and less disturbed configurations than the submm galaxies). Alternative explanations to mergers have been presented in the literature. They could be associated with planar structures in the galaxy formation process, or they could be structures generated by sequential star formation (Cowie, Hu & Songaila 1995).

Can we decide if an apparent clump of components, seen in many of our sources in Fig. 2, is truly a merger versus an assembly of HII regions in a large galaxy? We previously showed how SMMJ 141809.8 displays a striking difference between its rest-frame UV and Visible emission, a morphological K-correction, which is seen only rarely in more local galaxies (Hibbard & Vacc 1997; Abraham et al. 1999; Kuchinski et al. 2001; Windhorst et al. 2002). However the most infrared-luminous local galaxies often show different morphologies in rest-frame nearIR (Scoville et al. 2000; Dinh-V-Trung et al. 2001). We must question how the morphological K-correction might affect our interpretation of the submm galaxies. We must also address how much structure is being resolved out by HST, lost to surface brightness dimming at redshifts z ≫ 1. A well-studied local ULIRG, Mkn231 (Goldader et al. 2001), shows 75 kpc tidal tails (10′′ at the submm galaxy redshifts). While we expect to miss many such features from the strong surface brightness dimming effects at high-z, we note that many of the optical morphologies do exhibit signs of extension. Colley et al. (1996) first made the argument that faint clumps at the same z close on the sky may be part of a bigger galaxy, most of the underlying part not being visible due to SB-dimming (the knots are unresolved, so they only dim as ∝ (1+z^2)). Without redshifts and velocity information for individual components, we cannot claim any source is a merger in progress. However, if it is not a merger yet, then it will likely be a future merger when the pieces come together and violently relax (barring the unlikely situation that σ is large enough for the violent relaxation to never happen). Regardless of the interpretation, these objects are clearly star formation wrecks of some sort, consistent with the submm excess and plausibly young ages.

6. Conclusions

The HST-STIS images of submm galaxies have clearly identified many large, distorted, and plausibly multiple component, merger systems. The physical separations of components are larger than similar luminosity IRAS galaxies seen locally, suggesting that they may typically represent an earlier stage of the merger process. The faint (R' > 24) submm sources on average have a larger effective radius (R_50) than the general “field” sample defined within the same STIS images. They are also typically larger than the z ∼ 3 LBG population, defined in terms of R_50 or Petrosian radius. The rest frame UV extents and far-infrared estimated SFRs of these submm galaxies are consistent with predictions based on the maximal star formation rate density of 20 M_Sun kpc^-2 seen in local starburst galaxies.

Consideration of the field sources with comparable R_50 val-
ues often reveals highly elongated and distorted systems, some indistinguishable from the morphologies represented by the submm galaxies. Scaling by the source count of the submm galaxies at $> 5$ mJy (0.25 arcmin$^{-2}$) suggests that there are roughly $4 \times$ the number of field galaxies with similar magnitudes and morphologies to the submm galaxies which do not obviously generate the copious bolometric luminosities (they are undetected in the submm and radio images). Our analysis of the LBGs and NB-galaxies suggests that some of these field galaxies with morphologies similar to submm galaxies would be LBGs/NB-galaxies. It remains to be seen whether the bolometric luminosities of the largest, irregular galaxies in the field are generally larger than the other field galaxy populations.

We would like to thank Ian Smail and Andrew Blain for detailed suggestions and comments on the manuscript which greatly helped improve the paper. We also acknowledge the detailed suggestions of an anonymous referee. Based on observations made with the NASA/ESA Hubble Space Telescope, obtained [from the Data Archive] at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. These observations are associated with proposal #9174. Support for proposal #9174 (SCC, RW) was provided by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

REFERENCES

Mac Low, M.-M., Ferrara, A., 1998, LNP, 506, 559
Murphy, T., et al., 1996, AJ, 111, 1025
(1) SMM J123553.3+621338 A very extended galaxy with as many as 10 compact components arranged in a north-south assembly within 3.4″. Submm flux (Chapman et al. 2001b), radio flux (Richards 2000).

(2) SMM J123600.1+620254 Five knots along a curve indicate that this galaxy is possibly an edge-on merger. Submm flux (Chapman et al. 2001b), radio flux (Richards 2000).

(3) SMM J123616.2+621514 A trio of components suggest a system about to merge. To within the astrometric error, the brightest component appears to be aligned with the radio emission, a Chandra X-ray source (both hard and soft bands), and a K-band peak in the ground based (0.5″) image. Submm flux (Chapman et al. 2001b), radio flux (Richards 2000).

(4) SMM J123618.3+621551 While only the central source is radio identified, the additional clumps lying within 2″ are plausibly associated, suggesting an early stage merger. Submm flux (Chapman et al. 2001b), radio flux (Richards 2000).

(5) SMM J123621.3+621708 A strong radio peak with an extremely faint optical identification lies offset 2″ from a weaker radio peak associated with a north-south linear structure. Submm flux (Barger, Cowie, & Richards 2000), radio flux (Richards 2000).

(6) SMM J123622.7+621630 The radio centroid sits in a saddle of low surface-brightness emission amongst a spectacular edge-on merger exhibiting 5 brightness peaks within an extended linear structure. The source is detected by Chandra in the hard X-ray band, but not in the soft band. Submm flux (Barger, Cowie, & Richards 2000), radio flux (Richards 2000).

(7) SMM J123710.0+622649 This source has two radio sources lying within the SCUBA beam. The western source corresponds to a bright elliptical galaxy, the redshift of which is unknown. A photometric redshift from the available multiband imaging (B, V, I, K) suggests a z ~ 0.4 galaxy. There is no significant optical emission at the location of the eastern radio source. Submm flux (Chapman et al. 2001b), radio flux (Richards 2000).

(8) SMM J123713.9+621827 The radio peak is offset by 0.7″ from an isolated and compact optical source, showing some extent in the north-east. This source is a bright Chandra X-ray source, and is the strongest submm emitter in our sample (16 mJy). With a radio flux of 595 mJy, it is also the strongest radio emitter. This source is likely to be a heavily dust obscured AGN. Submm flux (Chapman et al. 2001b), radio flux (Richards 2000).

(9) SMM J131231.9+424430 A double extended source, with signs of low surface brightness features. This galaxy was detected at 6.7 μm using the ISO satellite by Sato et al. (2002), suggesting that many of these submm galaxies will be routinely detected by the SIRTF mission. Submm flux (Barger, Cowie & Sanders 1999), radio flux (E. Richards, private communication).

(10) SMM J131235.2+424424 This object is almost undetected, with only a faint 1.9σ peak rising above the noise at the radio position (omitted from Fig. 2). As the source was detected at I = 26.4 in ground based imagery, the HST may be resolving out a complex and diffuse structure. Submm flux derived from our own reduction of the archival SCUBA data, radio flux (E. Richards, private communication). The submm and radio fluxes are presented in the figures of Chapman et al. (2002c).

(11) SMM J141809.8+522205 An assembly of bright blobs, with low surface brightness intervening material. A bridge of emission connects the strongest two components. Spectroscopic redshifts have been obtained for all three central blobs, z = 2.99 (Chapman et al. 2002a – see this work also for radio and submm flux measurements). The original radio data in this region was presented in Fomalont et al. (1991). The UV spectroscopic redshift for the brightest R-band component is presented in Chapman et al. (2000). A strong K-band source lines up with northernmost blob, coincident with a millimeter interferometry measurement.

(12) SMM J221724.7+001242 A filamentary object, which appears like an irregular edge-on galaxy, flanked by two compact components. The galaxy is identified in the VLA B-array radio map and in the archival Chandra X-ray image. Lensing from the bright galaxy to the north-west may be subtly distorting the image (Chapman et al. 2002b). Fitting and subtracting the bright elliptical galaxy does not reveal any additional structure or components. The updated radio and submm fluxes for this source are presented in Chapman et al., (in preparation).

(13) SMM J221726.1+001239 This is the “blob-1” submm source (Steidel et al. 2000; Chapman et al. 2001b) lying at the center of a z = 3.09 proto-cluster. The HST image reveals a faint, apparently linear system, with surrounding very faint components which could represent a merger in progress. A brighter unresolved core along the linear structure suggests an AGN or a more concentrated starburst. While no significant radio emission has been detected to isolate the the position of the submm source, an interferometric detection of molecular gas in CO(4-3) identifies the submm emission with this HST source (Chapman et al. 2004). The radio and submm fluxes, and the spectroscopic redshift for this source are also detailed in (Chapman et al. 2004).
Table 1

Photometry and Morphology Indices for the Submm Galaxies

(a) Ground based I-mag in 3′′ aperture centered on radio position.
(b) HST mag down to 1.5σ ellipse isophot.
(c) Effective radius, down to 50% light contour.
(d) Concentration index.
(e) $b/a$ from intensity weighted moment.
(f) $b/a$ from least-squares fit of an ellipse out to the 1.5σ SB isophotal contour.
(g) mean surface brightness (SB – mag per arcsec$^2$) within the effective radius.
(h) image size (in arcsec) from the intensity weighted image moment.

<table>
<thead>
<tr>
<th>source</th>
<th>$S_{500\mu m}$ (mJy)</th>
<th>$S_{1.4GHz}$ (µJy)</th>
<th>$I^\prime$ (mag)</th>
<th>$R^\prime(573)^h$ (mag)</th>
<th>$R_{90}^\prime$ (′)</th>
<th>$C32^d$</th>
<th>$b/a^e$</th>
<th>$b/a^f$</th>
<th>SB$^g$ (mag/′′)</th>
<th>size$^h$ (′′)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) SMMJ123553.3+621338</td>
<td>8.8±2.1</td>
<td>58.4±9.0</td>
<td>24.84</td>
<td>25.48</td>
<td>0.50</td>
<td>1.32</td>
<td>0.32</td>
<td>0.60</td>
<td>24.80</td>
<td>0.5</td>
</tr>
<tr>
<td>(2) SMMJ123600.1+620254</td>
<td>6.9±2.0</td>
<td>262±17</td>
<td>24.67</td>
<td>26.04</td>
<td>0.34</td>
<td>1.39</td>
<td>0.62</td>
<td>0.34</td>
<td>25.19</td>
<td>0.6</td>
</tr>
<tr>
<td>(3) SMMJ123616.2+621514</td>
<td>5.8±1.1</td>
<td>53.9±8.4</td>
<td>24.46</td>
<td>26.70</td>
<td>0.41</td>
<td>1.42</td>
<td>0.59</td>
<td>0.71</td>
<td>26.24</td>
<td>0.3</td>
</tr>
<tr>
<td>(4) SMMJ123618.3+621551</td>
<td>7.8±1.6</td>
<td>151±11</td>
<td>24.98</td>
<td>26.66</td>
<td>0.14</td>
<td>1.51</td>
<td>0.88</td>
<td>0.52</td>
<td>24.31</td>
<td>0.4</td>
</tr>
<tr>
<td>(5) SMMJ123621.3+621708</td>
<td>7.5±2.3</td>
<td>148±11.0</td>
<td>23.42</td>
<td>26.70</td>
<td>0.19</td>
<td>1.41</td>
<td>0.42</td>
<td>0.53</td>
<td>24.16</td>
<td>0.5</td>
</tr>
<tr>
<td>(6) SMMJ123622.7+621630</td>
<td>7.1±1.7</td>
<td>70.9±8.7</td>
<td>24.32</td>
<td>25.27</td>
<td>0.36</td>
<td>1.38</td>
<td>0.42</td>
<td>0.58</td>
<td>24.32</td>
<td>0.5</td>
</tr>
<tr>
<td>(7) SMMJ123710.0+622649</td>
<td>7.4±2.2</td>
<td>551±31</td>
<td>21.15</td>
<td>22.43</td>
<td>0.50</td>
<td>1.48</td>
<td>0.63</td>
<td>0.59</td>
<td>23.43</td>
<td>0.7</td>
</tr>
<tr>
<td>(8) SMMJ123713.9+621827</td>
<td>15.7±2.4</td>
<td>595±31</td>
<td>26.80</td>
<td>27.19</td>
<td>0.17</td>
<td>1.58</td>
<td>1.00</td>
<td>0.72</td>
<td>25.30</td>
<td>0.2</td>
</tr>
<tr>
<td>(9) SMMJ131231.9+424430</td>
<td>3.8±0.8</td>
<td>127±7.0</td>
<td>25.36</td>
<td>27.00</td>
<td>0.36</td>
<td>1.23</td>
<td>0.86</td>
<td>0.69</td>
<td>26.70</td>
<td>0.3</td>
</tr>
<tr>
<td>(10) SMMJ131235.2+424424</td>
<td>3.9±0.9</td>
<td>34.1±7.1</td>
<td>26.05</td>
<td>28.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(11) SMMJ141809.8+522205</td>
<td>5.4±1.4</td>
<td>&lt; 58</td>
<td>24.57</td>
<td>24.14</td>
<td>0.38</td>
<td>1.19</td>
<td>0.70</td>
<td>0.73</td>
<td>23.75</td>
<td>0.6</td>
</tr>
<tr>
<td>(12) SMMJ221724.7+001242</td>
<td>13.2±3.0</td>
<td>120±34.0</td>
<td>25.21</td>
<td>25.78</td>
<td>0.37</td>
<td>1.38</td>
<td>0.35</td>
<td>0.75</td>
<td>24.47</td>
<td>0.6</td>
</tr>
<tr>
<td>(13) SMMJ221726.1+001239</td>
<td>17.8±2.3</td>
<td>&lt; 53</td>
<td>26.11</td>
<td>26.82</td>
<td>0.38</td>
<td>1.47</td>
<td>0.41</td>
<td>0.27</td>
<td>25.76</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 1

CAS Morphology Indices for the Submm Galaxies

<table>
<thead>
<tr>
<th>source</th>
<th>concentration</th>
<th>asymmetry</th>
<th>$R_{Petrosian}$ (′)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) SMMJ123553.3+621338</td>
<td>3.26</td>
<td>0.14</td>
<td>2.09</td>
</tr>
<tr>
<td>(2) SMMJ123600.1+620254</td>
<td>3.47</td>
<td>0.10</td>
<td>1.39</td>
</tr>
<tr>
<td>(3) SMMJ123616.2+621514</td>
<td>3.91</td>
<td>0.47</td>
<td>1.23</td>
</tr>
<tr>
<td>(4) SMMJ123618.3+621551</td>
<td>3.73</td>
<td>0.35</td>
<td>1.20</td>
</tr>
<tr>
<td>(5) SMMJ123621.3+621708</td>
<td>3.92</td>
<td>0.05</td>
<td>4.05</td>
</tr>
<tr>
<td>(6) SMMJ123622.7+621630</td>
<td>3.43</td>
<td>0.05</td>
<td>2.61</td>
</tr>
<tr>
<td>(7) SMMJ123710.0+622649</td>
<td>3.93</td>
<td>0.12</td>
<td>0.72</td>
</tr>
<tr>
<td>(8) SMMJ123713.9+621827</td>
<td>3.87</td>
<td>0.11</td>
<td>0.71</td>
</tr>
<tr>
<td>(9) SMMJ131231.9+424430</td>
<td>2.01</td>
<td>0.16</td>
<td>1.05</td>
</tr>
<tr>
<td>(10) SMMJ131235.2+424424</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>(11) SMMJ141809.8+522205</td>
<td>3.02</td>
<td>1.05</td>
<td>0.73</td>
</tr>
<tr>
<td>(12) SMMJ221724.7+001242</td>
<td>3.01</td>
<td>0.23</td>
<td>7.63</td>
</tr>
<tr>
<td>(13) SMMJ221726.1+001239</td>
<td>2.12</td>
<td>0.39</td>
<td>0.84</td>
</tr>
</tbody>
</table>
**Figure 1.** — $I$-band magnitude distributions of the parent sample of submm galaxies identified through their radio distribution (line histogram – from Chapman et al. 2003b), compared with the $I$-mags of the HST sample considered here (shaded histogram). The faintest bin of the parent sample represents mostly lower limits to the $I$-band flux. The HST sources appear representative of the parent distribution.

**Table 3**

Qualitative Classifications for Submm Galaxies, LBGs, and Narrow-Band Galaxies

<table>
<thead>
<tr>
<th>Classification</th>
<th>Submm galaxies</th>
<th>LBGs</th>
<th>NB-galaxies</th>
</tr>
</thead>
<tbody>
<tr>
<td>compact regular</td>
<td>2 (17%)</td>
<td>20 (44%)</td>
<td>8 (27%)</td>
</tr>
<tr>
<td>compact irregular</td>
<td>0 (0%)</td>
<td>15 (33%)</td>
<td>10 (33%)</td>
</tr>
<tr>
<td>elongated regular</td>
<td>0 (8%)</td>
<td>2 (30%)</td>
<td>1 (3%)</td>
</tr>
<tr>
<td>elongated irregular</td>
<td>3 (25%)</td>
<td>5 (11%)</td>
<td>8 (27%)</td>
</tr>
<tr>
<td>irregular, multiple component</td>
<td>7 (58%)</td>
<td>3 (7%)</td>
<td>3 (10%)</td>
</tr>
</tbody>
</table>
FIG. 2.— HST-STIS observations of submm galaxies (6′′ fields). Radio centroids are indicated with cross-hairs. Redshifts are photometric (submm/radio – Carilli & Yun 1999, 2000) except as indicated with an asterisk (spectroscopic) or in brackets (the redshift of the nearby elliptical). All images except source 7 have been smoothed with a gaussian FWHM 0.05′′ for better visibility.
Fig. 3.— Apparent nuclear separations for the submm galaxies (solid line) compared to the 1 Jy sample of IRAS galaxies from Veilleux, Kim & Sanders (2002—see also Murphy et al. 1996) (dashed line). The submm histogram binning is twice as large as for the IRAS sample. The distribution of local IRAS galaxies is highly peaked at small values but has a significant tail at higher values. The submm galaxies all have separations of $>5$ kpc except sources (7) and (8) which do not exhibit multiple component or extended structures.
FIG. 4.—HST-STIS derived morphological parameters for the submm galaxies (left panels) (submm galaxies – circles; field galaxies – squares; stars – stars). For comparison, we show the same parameters for the Lyman-break galaxies (diamonds) and $z \sim 3.1$ narrow-band Lyα galaxies (crosses) in the right panels. **Upper row:** effective radius ($R_{50}$) as a function of total magnitude; **Middle row:** Concentration index ($C_{32} = $ ratio of 75% to 25% quartile sizes) vs. magnitude. Higher $C_{32}$ means more compact. **Lower row:** the mean surface brightness within the effective radius (mag/arcmin$^2$) versus semi-major axis radius in arcsec.
Fig. 5 — HST-WFPC2 observations of Lyman-break galaxies (6′′ fields). Galaxies will have redshifts lying within the LBG selection function of $z=2.5–3.5$ (Steidel et al. 1999). The pixel size is 0.1′′ for these images. As the sources are generally brighter than the submm galaxies, and the pixel scale is larger, the images have been left unsmoothed to preserve extended structure.
Fig. 6.— HST-WFPC2 observations of $z \sim 3.1$ sources selected as narrow-band Ly$_\alpha$ excess objects, as described in Steidel et al. (2000). Field size is 6″. As the narrow-band galaxies are generally near the detection limit of the WFPC2 imagery, the images have been smoothed with a gaussian FWHM 0.05″ for better visibility. The location of the narrow-band source has been indicated with the cross-hatch.
Fig. 7.— A plot of concentration index (C) and asymmetry (A) for both LBGs in the HDF from z=2–3 (circles) and submm galaxies (triangles). The submm galaxies are significantly more concentrated than the LBGs. The asymmetries are similar for the submm galaxies and LBGs.