A MORPHOLOGICAL STUDY OF GAMMA-RAY BURST HOST GALAXIES

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ABSTRACT

We present a comprehensive study of the morphological properties of 42 γ-ray burst (GRB) host galaxies imaged with the Hubble Space Telescope in the optical band. The purpose of this study is to understand the relation of GRBs to their macroenvironments and to compare the GRB-selected galaxies to other high-redshift samples. We perform both qualitative and quantitative analyses by categorizing the galaxies according to their visual properties and by examining their surface brightness profiles. We find that the majority of the galaxies have approximately exponential profiles, indicative of galactic disks, and have a median effective radius of about 1.7 kpc; ~20% of the hosts are better fit with a bulge-dominated profile. Inspection of the visual morphologies reveals a high fraction of merging and interacting systems, with ~30% showing clear signs of interaction and an additional 30% exhibiting irregular and asymmetric structure, which may be the result of recent mergers; these fractions are independent of redshift and galaxy luminosity. The fraction of mergers appears to be elevated compared to other high-redshift samples (i.e., the HDF), particularly for the low luminosities of GRB hosts ($M_B \sim -16$ to $-21$ mag). Finally, we show that GRB hosts clearly follow the size-luminosity relation present in other galaxy samples, but thanks to spectroscopic absorption redshifts they help to extend this relation to fainter luminosities.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: structure — gamma rays: bursts

1. INTRODUCTION

For nearly a century astronomers have attempted to classify galaxies by their apparent shapes and to draw conclusions about the process of galaxy formation and evolution from these morphologies. The basic Hubble classification (Hubble 1926) and its variants (e.g., Hubble 1936; Sandage 1961) divide galaxies into three broad categories: elliptical, disk, and irregular. This morphological classification correlates with, among other physical properties, the star formation activity of the galaxies, at least in the nearby universe. Studies of local galaxy samples (Schweizer 1986), as well as the currently favored cold dark matter (ΛCDM) model (Mihos & Hernquist 1996), also suggest that interactions and mergers play an important role in the buildup of galactic and stellar mass, both through the accretion of material and an increase in the star formation rate. Thus, the morphological properties of galaxies as a function of cosmic time provide direct insight into the physical processes governing galaxy evolution.

In this manner, analysis of deep fields obtained primarily with the Hubble Space Telescope (HST) suggests that the locally defined Hubble sequence may begin to break down at $z \sim 1$ (e.g., review by van den Bergh 2002 and referenced therein) with the emergence of a sizable fraction of faint, irregular, and interacting systems (e.g., Driver et al. 1995; Ellis 1997). While these observations, along with observations of local galaxies (e.g., Arp 1966), suggest that mergers play a significant role in the formation of galaxies, four important limitations prevent a conclusive connection between morphology and galaxy formation at higher redshift.

First and foremost, studies of galaxy morphologies rely on flux-limited samples, which may contain a large fraction of atypical objects; e.g., ultraluminous submillimeter galaxies (Chapman et al. 2003) or $R < 25$ mag optically selected galaxies (Conselice et al. 2003). Second, it is not clear how to relate the various samples (e.g., Lyman break galaxies, submillimeter-selected galaxies, and near-IR-selected galaxies) to each other. This is partly because of the different selection techniques and the differences in observed properties and space densities. Third, at faint fluxes ($R \sim 25$ mag), where irregular galaxies may dominate the population, the distance scale relies on photometric redshifts, whose accuracy is difficult to assess. Finally, redshift-dimming effects, $\propto (1+z)^{3}$, lead to an underestimate of the contribution of low surface brightness components.

In this context, it is interesting to investigate the morphological properties of γ-ray burst (GRB) host galaxies. We now have conclusive evidence that GRBs mark the death of massive stars (Stanek et al. 2003) and therefore pinpoint star-forming galaxies at all redshifts (Hogg & Fruchter 1999; Bloom et al. 2002; Christensen et al. 2004). This allows a uniform selection over a wide range of redshift and luminosity. In addition, absorption spectroscopy of the bright afterglows allows us to measure redshifts of arbitrarily faint galaxies. Thus, the current GRB host sample spans $z \sim 0.1$–4.5 and $M_B \sim -16$ to $-21$ mag (i.e., 0.01$L_*$ to $L_*$).

Here we present a comprehensive analysis of all optical HST observations of GRB host galaxies (see also Conselice et al. 2005). The purpose of this study is twofold: first, to obtain information on the large-scale environments in which GRBs occur, as a clue to the formation of the progenitors, and, second, to survey a set of high-redshift galaxies that are physically related by their star formation activity, but that alleviate some of the selection effects of other samples. We summarize the HST observations in § 2, provide a quantitative (§ 3) and qualitative (§ 4) analysis of the host morphologies, and compare the results to other high-redshift galaxy samples (§ 5). We show that, despite an overall diversity in the sizes and luminosities of GRB hosts, they mostly have roughly exponential profiles, with a large fraction appearing to undergo mergers and interactions. Throughout the paper we use the standard cosmological parameters, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, and $\Omega_{\Lambda} = 0.73$ (Spergel et al. 2003).

2. HUBBLE SPACE TELESCOPE DATA

We retrieved data from the HST archive for all available GRBs after on-the-fly preprocessing. These include 29 GRBs observed...
| GRB (1) | z (2) | Instrument (3) | Filter (4) | Exposure Time (s) (5) | Date (6) | $n$ (arsec) (7) | $r_e$ (kpc) (8) | $\chi^2$ (9) | AB Magnitude (mag) (10) | $M_B$ (mag) (11) | Classification (12) | Classification (13) |
|---------|------|---------------|-----------|----------------------|---------|----------------|----------------|----------|------------------------|----------------|---------------------|---------------------|
| 970228. | 0.695 | STIS           | CL        | 2300                 | 1997 Sep 4 | 1.0            | 0.36           | 2.53      | 0.67                  | 24.7 ± 0.1 | -18.2               | DI                  |
| 970508. | 0.835 | STIS           | CL        | 11568                | 1998 Aug 5 | 1.2            | 0.31           | 2.53      | 0.91                  | 25.0 ± 0.15 | -17.9               | BL                  |
| 970828. | 0.958 | WFPC2          | F606W     | 3300                 | 2001 Aug 16| ...            | 0.6            | 3.66      | 0.66                  | 24.9 ± 0.05 | ...                 | ...                 |
| C1      | ...   | ...            | ...        | ...                  | ...       | 0.4            | 0.25           | 1.99      | 0.66                  | 25.9 ± 0.15 | ...                 | ...                 |
| C2      | ...   | ...            | ...        | ...                  | ...       | 0.6            | 0.16           | 1.27      | 0.66                  | 25.8 ± 0.15 | ...                 | ...                 |
| C3      | ...   | ...            | ...        | ...                  | ...       | 0.7            | 0.54           | 4.29      | 0.72                  | 23.6 ± 0.1 | ...                 | ...                 |
| C4      | ...   | ...            | ...        | ...                  | ...       | 0.2            | 2.1            | 4.21      | 0.72                  | 24.4 ± 0.1 | ...                 | ...                 |
| C5      | ...   | ...            | ...        | ...                  | ...       | 0.5            | 0.28           | 2.23      | 0.72                  | 25.4 ± 0.15 | ...                 | ...                 |

**Observations and Morphological Properties of GRB Host Galaxies**

**Table 1**

| z   | Instrument | Filter | Exposure Time | Date | $n$ (arsec) | $r_e$ (kpc) | $\chi^2$ | AB Magnitude (mag) | $M_B$ (mag) |
|-----|------------|--------|---------------|------|-------------|-------------|----------|-------------------|-------------|
| 0.020321 | STIS | CL | 2300 | 1997 Sep 4 | 1.0 | 0.36 | 2.53 | 0.67 | 24.7 ± 0.1 | -18.2 |
| 0.020305 | STIS | CL | 11568 | 1998 Aug 5 | 1.2 | 0.31 | 2.53 | 0.91 | 25.0 ± 0.15 | -17.9 |
| 0.020127 | STIS | CL | 6586 | 2003 Jan 20 | 1.4 | 0.15 | 0.81 | 25.7 ± 0.15 | -26.4 |
| 0.020124 | STIS | CL | 7418 | 2002 Apr 6 | 1.0 | 0.11 | 1.02 | 26.6 ± 0.2 | ... |

**Notes:**

- $n$ and $r_e$ are measured in arcseconds and kiloparsecs, respectively.
- $\chi^2$ is the reduced chi-square.
- AB Magnitude and $M_B$ are in magnitude.
- Classification includes morphological types such as elliptical (E), spiral (S), and irregular (I).

**Abbreviations:**

- STIS: Space Telescope Imaging Spectrograph
- WFPC2: Wide Field Planetary Camera 2
- HST: Hubble Space Telescope

**Column Headings:**

- GRB: GRB (Gamma-Ray Burst) Number
- z: Redshift
- Instrument: Telescope/Instrument
- Filter: Filter used for observation
- Exposure Time: Exposure time in seconds
- Date: Date of observation
- $n$: Size parameter in arcseconds
- $r_e$: Effective radius in kiloparsecs
- $\chi^2$: Reduced chi-square
- AB Magnitude: Absolute magnitude
- $M_B$: Absolute B magnitude
- Classification: Classification of the host galaxy

**Table Entries:**

- For STIS observations, filters are CL (clear), F450W, F606W, F814W, and F850LP.
- For WFPC2 observations, filters are F606W and F814W.
with the Space Telescope Imaging Spectrograph (STIS), 8 GRBs observed with the Wide-Field Planetary Camera 2 (WFPC2/WF3), and 10 GRBs observed with the Advanced Camera for Surveys (ACS/WFC). Details of the observations are summarized in Table 1. For each GRB we used the latest available images to reduce contamination from the afterglow and/or supernova emission.6

We processed, distortion-corrected, and combined individual exposures using the IRAF tasks drizzle and multidrizzle (STIS and WFPC2) and subject itself to morphological classification (see §3 for definitions). Magnitudes were determined using the IRAF task phocont, and errors include a systematic contribution in the uncertainty in the choice of aperture size.

In Figures 1 and 2 we show gray-scale and color images of the individual host galaxies. All images are flux-calibrated in the AB system according to the zero points listed in the instrument handbooks (see also Sirianni et al. 2005) and are corrected for Galactic extinction (Schlegel et al. 1998). For GRB 011121 we use the extinction value determined by Price et al. (2002) from observations of the afterglow.

6 Residual afterglow and/or supernova emission is detected in GRBs 970228, 991216, 030329, and 041006.
We note that the use of various filters, as well as the dispersion in GRB host redshifts, results in a mix of rest-frame bands. Still, the majority of the source are located at \( z \approx 1 - 2 \) and were observed at roughly 6000 Å, corresponding to the rest-frame near-UV.

3. MORPHOLOGICAL CLASSIFICATION

To classify the morphological properties of the GRB host galaxies, we created eight different qualitative morphological categories. Each category is independent of the others, and galaxies may fit into more than one category. In this manner, we are able to place a large number of galaxies into individual categories and account for multiple features. The categories are concentrated elliptical or circular structure or bloblike (BL) structure, conspicuous disk structure (DI), highly asymmetric or irregular structure (AS), galactic structure containing knots (KN), galaxies with off-center peaks (OC), galaxies with tidal tails (TT), galaxies that are either undergoing mergers or are closely interacting (MI), and galaxies that are too faint for morphological analysis (TF). The classification has been carried out independently by C. W. and E. B., and the results are summarized in Tables 1 and 2.

Of the 45 host galaxies observed with HST, three are not detected in our images (980326, 020124, and 020322), and an additional...
four are too faint to accurately categorize (980519, 990308, 990510, and 000301C). These galaxies occur either at unknown redshifts or at $z > 1.5$. While these galaxies cannot be classified morphologically, they do indicate that a nonnegligible fraction of GRBs occurs in low-luminosity and/or low surface brightness systems. In fact, given the measured redshifts and the magnitude limits for these galaxies, we find that they typically have an absolute rest-frame $B$-band magnitude of $M_B \approx -17$ mag, somewhat fainter than the Large Magellanic Cloud.

For the remaining 38 galaxies with morphological classification, we combine the basic categories into two general groups: regular and irregular/interacting. Regular galaxies are those that are categorized exclusively as either blob- or disklike. The primary difference between these two categories is that the bloblike galaxies have much higher luminosity concentrations, while the disklike galaxies have symmetric extended features. In § 4 below we show that both the BL and DI galaxies have surface brightness distributions that are well described by exponential profiles and can therefore be

### TABLE 2

| Redshift Range | AS | KN | OC | TT | MI | DI | BL | TF | Regular | Irregular | Total Galaxies |
|----------------|----|----|----|----|----|----|----|----|----------|------------|----------------|
| $z < 1.0$................. | 2  | 2  | 3  | 1  | 4  | 5  | 3  | 0  | 5        | 9          | 14             |
| $z > 1.0$................. | 4  | 3  | 2  | 4  | 5  | 1  | 5  | 2  | 5        | 9          | 16             |
| Unknown $z$.............. | 2  | 1  | 4  | 4  | 3  | 1  | 2  | 2  | 8        | 12         | 20             |
| Total..................... | 8  | 6  | 9  | 9  | 13 | 9  | 9  | 4  | 12       | 26         | 42             |

**Note.**—Summary of morphological classification for the GRB host galaxy sample (see § 3 for definitions).
classified as disk galaxies. The regular galaxies make up about 30%--40% of the total sample.

The irregular category includes galaxies that are asymmetric or show signs of a merger or interaction. The latter includes multiple bright galaxies (e.g., the hosts of GRB 020405 and XRF 020903) or galaxies with filamentary structures (interpreted as tidal tails) extending toward nearby galaxies with which they are interacting (e.g., the host of GRB 000926). These tails are not symmetric about the center of the light distribution.

A similar morphology is evident in the OC category, for which the extended low surface brightness emission is not likely to be part of an ordered disk structure. The majority of these galaxies do not have visible galactic neighbors. If they are the results of galactic mergers, then they are most likely in the late stages of the merging process, or, alternatively, signal an interaction with a lower mass galaxy. In this context, the environment of GRB 991208 may be of particular interest. A faint galaxy ∼7 kpc from the host galaxy exhibits a tidal tail morphology, suggesting that the host is interacting with a low-mass companion. It is also interesting to note that the host of GRB 991208, with $M_B \approx -18.2$ mag, is similar in brightness to the LMC, suggesting that this is a merger between two dwarf galaxies; an illustrative local example is NGC 1487, which is an interacting system of two dwarf galaxies (Johansson & Bergvall 1990).

The asymmetric galaxies exhibit clumpiness or concavities in their light distribution, which may be interpreted as the result of an interaction. However, this morphology may also be interpreted as clumpiness in the distribution of the star formation activity, particularly in the case of higher redshift hosts, for which we sample the rest-frame UV light. We note that the latter explanation may be partially supported by the lack of obvious nearby companions, although, as in the case of the OC galaxies, these systems may be in the late stages of merging. The same argument holds for galaxies exhibiting knots, which could be the remnant bright cores of merging galaxies or signs of patchy star formation activity. A relevant example is the host of GRB 990705. This galaxy exhibits pronounced spiral structure with bright knots of star formation. At lower surface brightness (or higher redshift), the spiral arms may not be detected and the system might appear to have a knot morphology. This effect may be possible here, given the roughly uniform exposure times for all host galaxies, despite the wide range in redshift (and hence surface brightness, which varies by a factor of 16 between $z = 0.5$ and 2).

For the galaxies with a morphological classification, the ratio of irregular and merging or interacting systems to regular systems is about 2:1, with an uncertainty of about 50%, most of which is due to small-number statistics. This ratio does not change significantly as a function of redshift. Dividing the sample into $z < 1$ (low $z$) and $z > 1$ (high $z$), we find that at low $z$ regular galaxies account for about 40% of the sample, while 60% are irregular. For the high-$z$ sample, the fractions are 30% and 60%, respectively, with the remainder being too faint. The only two categories with possible evolution between the low- and high-$z$ samples are the tidal tails and disks. Tidal tails occur in about 10% of the low-$z$ population, but appear in 25% of the high-$z$ population, while disk galaxies make up 40% of the low-$z$ population and only 10% of the high-$z$ population. See Figure 3 for a visual representation of this data and its associated error.
There are 10 galaxies in our sample that have a morphological classification but no redshift information. The ratio of regular to irregular galaxies in this subsample is 1:4, which is similar (within the small-number uncertainties) to the ratio in the rest of the sample. We note that due to their faintness, these galaxies are more likely to reside at \( z > 1 \), which may slightly elevate the fraction of irregulars at high redshift, although this does not significantly change the overall 2:1 ratio.

We finally note that some ambiguity exists among our broad classifications. For example, the host of GRB 990123 may be interpreted as a merger/interaction with strong tidal tails, where the burst itself occurred in the disrupted galaxy. Alternatively, this galaxy may be classified as a disk galaxy with a bright spiral arm accentuated by bright knots, which are presumably star-forming regions. In this case, the burst was located in one of these bright knots. Still, such cases account for a relatively small fraction of the overall sample. The ambiguities tend to arise when classifying particular types of irregular structure or when determining whether a galaxy is disklike or bloblike.\(^{8}\) Therefore, they have little effect on the overall numbers of regular and irregular galaxies.

3.1. Classification of Galaxies in the HDF

In order to compare our sample to other high-redshift populations, we performed an identical visual classification on galaxies with known redshifts in the Hubble Deep Field (HDF; Williams et al. 2000). We obtained the reduced HDF images from the Space Telescope Science archive.\(^9\) The images were taken in the F450W, F606W, and F814W filters. We performed the classification on a color composite image. All redshift information comes from a survey performed by Cohen et al. (2000). The results of this classification are summarized in Table 3 and shown in Figure 3.

Unlike the GRB host galaxies, the galaxies in the HDF show evolution from low to high redshift in almost all morphological categories. The frequencies of galaxies categorized as asymmetric, off-center, having tidal tails, or undergoing a merger or interaction increase from low \( z \) to high \( z \). In particular, the proportion of merging/interacting galaxies at high redshift is almost 4 times that of the proportion at low redshift. The proportion of bloblike galaxies increases by a factor of 1.5 at high redshift, but the proportion of disklike galaxies decreases by a factor of 3. Only the knot category shows no significant change between the low- and high-redshift populations. Overall, the ratio of irregular to regular galaxies is about 1:4 at \( z < 1 \), and about 2:1 at \( z > 1 \), as opposed to a nearly constant fraction of up to 2:1 for the GRB host galaxies. A similar morphological study relating GRB host galaxies to galaxies in the HDF was performed by Conselice et al. (2005). See \( \S \) 5 for a comparison to their results.

Note that, due to spectroscopic redshift limitations, the galaxies in the HDF sample are generally somewhat brighter than the galaxies in the GRB sample. Also, the HDF images are much less noisy than those used in the GRB sample. These two effects can lead to several biases in our results. Since the HDF galaxies have relatively high luminosity limitations, their morphologies may not be representative of average field galaxies. Unfortunately, this is not an error for which we can easily correct. We expect that the higher signal-to-noise ratio in the HDF sample allows us to identify irregular galaxy structures more easily. Therefore, our data may underestimate the fraction of irregular GRB host galaxies compared to irregular HDF galaxies. We do not expect biases in the HDF sample to significantly change with redshift, so our discussion on morphological evolution should be unaffected.

4. SURFACE BRIGHTNESS PROFILES

Observations of local galaxies suggest that the surface brightness profiles of disk galaxies are roughly exponential, while those of elliptical galaxies and galaxy bulges tend to follow an \( r^{1/4} \) de Vaucouleurs law (de Vaucouleurs 1948). In this section we determine the surface brightness profiles and sizes of the GRB host galaxies and investigate their distributions as an additional input into their morphological classification. We determine the radial surface brightness distributions in two ways. First, we construct radial surface brightness plots using the IRAF task \texttt{ellipse}, with a range of isophotes that spans the full extent of each host galaxy. The resulting surface brightness profiles are shown in Figures 4 and 5.

None of the well-resolved host galaxies with high signal-to-noise detections exhibit a clear \( r^{1/4} \) profile, confirming their nature as disk and irregular galaxies. With the exception of the host galaxy of GRB 991208, all the galaxies are well resolved relative to the instrumental point-spread function as measured from stars in the field (Figs. 4 and 5). We thus fit the surface brightness profiles of all systems with an exponential disk, \( \Sigma(r) = \Sigma_0 \exp (-r/r_e) \), leaving the central surface brightness (\( \Sigma_0 \)) and the scale length (\( r_e \)) as free parameters. We find that the scale length distribution peaks at \( r_e \approx 0.09'' \), with a tail extending to \( \sim 0.35'' \). We note that our surface brightness profiles are in good agreement with those presented recently by Conselice et al. (2005), and minor differences may be due to the use of extrapolated I-band magnitudes in Conselice et al. (2005) compared to our AB magnitudes.

Our second approach in studying the surface brightness profiles is to use the GALFIT software (Peng et al. 2002). This allows us to fit all but the most irregularly shaped galaxy (GRB 020405). In this case we use the Sersic function (Sersic 1968)

\[
\Sigma(r) = \Sigma_e \exp \left\{ -\kappa (r/r_e)^{1/n} - 1 \right\},
\]

where \( n \) is the concentration parameter (\( n = 1 \) is equivalent to an exponential profile), while \( n = 4 \) is the de Vaucouleurs profile, \( \kappa \) is a constant that is coupled to the value of \( n, r_e \) is the effective radius, and \( \Sigma_e \) is the surface brightness at \( r = r_e \). We

\(^8\) This latter ambiguity primarily occurred in the HDF sample.

\(^9\) See http://www.stsci.edu/ftp/science/hdf/archive/mosaics.html.

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### TABLE 3

| Redshift Range | AS | KN | OC | TT | MI | DI | BL | TF | Regular | Irregular | Total Galaxies |
|----------------|----|----|----|----|----|----|----|----|---------|-----------|----------------|
| \( z < 1.0 \) | 16 | 10 | 10 | 8  | 3  | 3  | 6  | 4  | 20      | 14        | 31             |
| \( z > 1.0 \) | 53 | 28 | 14 | 31 | 45 |
| Total         | 69 | 44 | 30 | 62 | 62 | 62 | 30 | 20 | 74      | 59        | 133            |

**Note:** Summary of morphological classification for galaxies with known redshifts in the Hubble Deep Field (see \( \S \) 3 for definitions).
generated point-spread functions for the individual instruments and filters using the Tiny Tim software package,\textsuperscript{11} assuming a power-law spectrum $F \propto \nu^{-1}$, which is roughly appropriate for the observed color distribution of GRB host galaxies (Berger et al. 2003), and a sampling fraction appropriate to the pixfrac values in §2. In all cases we find adequate fits to the host galaxies, with $\chi^2_\nu \approx 0.5$–2 per degree of freedom. We note that some sources, particularly at low signal-to-noise ratio, can be adequately fit with a range of $n \approx 1$–4. For sources with complex morphology (e.g., XRF 020903) or contaminating point sources (e.g., GRB 011121) we use multiple components to account for substructure. The resulting values of $n$ and $r_e$ are listed in Table 1.

In Figure 6 we plot the distribution of $r_e$ and $n$ for the hosts with an accurate value of $n$. For the 10 hosts without known redshifts, we take advantage of the flat evolution of the angular diameter distance with redshift and assume a value of 8 kpc arcsec$^{-1}$, appropriate for $z \approx 1$–3. The distribution of $n$ is strongly peaked around a value of $\sim 1$, indicating that GRB hosts are well described as exponential disks. As noted in other studies (e.g., Ravindranath et al. 2004), $n \leq 2$ is an efficient criterion for disk-dominated galaxies. The distribution of $r_e$ ranges from about 0.3 to 10 kpc, with a peak at $r_e \approx 1.7$ kpc. As shown in Figure 7, we do not find any correlation between $r_e$ and $n$ or redshift, although we note that there is a larger dispersion in $r_e$ for $z \leq 1$. This may be a result of surface brightness dimming, which would tend to make higher redshift objects appear more compact.

A comparison to the morphological analysis of galaxies in the FIRES data (Trujillo et al. 2004, 2006) suggests that the distributions of $n$ values are similar, except that the latter exhibit a tail at $n \gtrsim 3$ (elliptical galaxies), which may not be present in the GRB sample. The distribution of effective radii, however, peaks at a large value compared to the GRB sample. To provide a direct comparison, we corrected the values given in Trujillo et al. (2004, 2006) for ellipticity and for the systematic overestimate of about 15% compared to GALFIT results (see Fig. 4 of Trujillo et al. 2004). The median effective radius of the FIRES galaxies is about a factor of 2 higher than that of the GRB sample.

\textsuperscript{11} See http://www.stsci.edu/software/tinytim/tinytim.html.
Fig. 6.—Histograms of the effective radius ($r_e$), the Sersic profile parameter $n$, and the redshifts for GRB host galaxies (hatched histogram) and for galaxies from the FIRES survey (Trujillo et al. 2004, 2006; thin line histogram). The histograms for the FIRES galaxies are renormalized to the number of GRB host galaxies. The distribution of $n$ is sharply peaked around a value of 1, suggesting that GRB host galaxies are well described by exponential disks. In addition, GRB host galaxies are on average a factor of 2 smaller compared to the FIRES galaxies. Median values are shown in each panel.

Fig. 5.—Radial surface brightness profiles for GRB host galaxies observed with WFPC2 and ACS. The dotted lines show the instrumental point-spread function of WFPC2 and ACS, as measured from several stars in the field. Clearly, all of the GRB host galaxies are well resolved. The dashed lines show exponential disk fits to the data.
hosts, which is possibly missing at higher redshift due to surface brightness dimming. There is a clear trend between exponential disks (than the FIRES sample. This is not surprising, given that several lines of evidence show that the pro-
genitors of GRB are massive stars. At high redshift, the proportion of irregular to regular galaxies is about 2
in both populations. This
suggests that high-redshift galaxies have higher masses than typical high-redshift field gal-
axies. Conselice et al. (2005) also find that low-redshift GRB hosts are smaller than low-redshift galaxies in the HDF, while the average sizes of high-redshift galaxies in the two samples is roughly the same.

Clearly, our morphological classification scheme produces different results than those obtained by measuring the concentration and asymmetry of the galaxies. Instead of finding differences between the GRB sample and the HDF sample at high redshifts, we find the samples to be similar at high redshift and to differ at low redshift. However, our results do not completely conflict with those of Conselice et al. (2005). They find that galaxy size differs most at low redshift, much like our morphological classification. Also, their conclusion that high-redshift galaxies are relatively massive agrees with our findings. Since we find little morphological difference between GRB host galaxies and field galaxies at high redshift and we assume that our classification is independent of galaxy mass and concentration, then it is likely that the GRB host galaxies at high redshifts are just galaxies with large masses and proportion-
ally high rates of star formation and GRB production.

As shown in § 4, the bulk of the galaxies have exponential surface brightness profiles. There are a few minor exceptions in low signal-to-noise filters, as well as in the case of GRB 021004, for which we find an adequate fit with an $r^{1/4}$ profile using GALFIT; a fit with $n = 1$ is equally adequate. Except for GRB 990705 and possibly GRB 990123, none of the GRB host galaxies exhibit clear signs of spiral structure. This includes, in particular, the several hosts at $z < 0.5$, for which such structures should be easily detected. Conselice et al. (2004) show that spiral and bar structures should be visible at redshifts as high as $z \sim 2$, with exposure times similar to our deep observations. The lack of clearly ordered spiral structure in GRB hosts may point to a violent merger history, which suppresses the emergence of spiral arms or is related to their low luminosities (Fig. 7).

The observed size-luminosity correlation presented in Figure 7 is in good agreement with that observed in other galaxy samples (e.g., Trujillo et al. 2006). However, the GRB sample extends this relation to lower luminosities due to the availability of absorption
redshifts that are not subject to the same brightness limit for spectroscopy imposed on flux-limited surveys. This is evident in the plot of absolute magnitude as a function of redshift shown in Figure 7.

Three of the galaxies in our sample, GRBs 980703, 000418, and 010222, exhibit high luminosity at submillimeter and/or radio wavelengths (Berger et al. 2001; Frail et al. 2002; Berger et al. 2003). Contrary to the trend observed in field submillimeter-selected galaxies (Chapman et al. 2003; Conselice et al. 2003), all three are highly symmetric and show no clear sign of interaction. Each was categorized as a bloblike galaxy, while GRB 980703 was additionally categorized as off-center. However, it has the most modest deviation of any of the off-center galaxies in our sample.

In comparison, HST observations of bright submillimeter-selected galaxies indicate a merger fraction of ~40%–80% (Conselice et al. 2003) and a low percentage (≤20%) of symmetrically shaped galaxies (Chapman et al. 2003). These three galaxies are also significantly bluer and less luminous than the typical submillimeter-selected galaxies (Berger et al. 2003). With only three objects, it is difficult to draw firm conclusions, but if this trend is supported by future observations, it may suggest that GRB-selected submillimeter galaxies tend to be bluer and more regular than field submillimeter galaxies.

On the whole, it appears that a large fraction of the GRB host galaxies show evidence of merging or interaction (30% show direct signs of interaction and an additional 30% show indirect signs of interaction). This proportion appears to be independent of both redshift and luminosity. In other high-redshift surveys, the proportion of interacting galaxies increases with galaxy brightness (Conselice et al. 2003) and with redshift (e.g., HDF). These results suggest that some physical process, for example, a preference for low metallicity or a young stellar population, causes GRBs to be overrepresented in faint merging systems. Overall, the high fraction of galaxies that show signs of merging and interaction suggest that these are regions of elevated star formation activity and that GRBs are less likely to occur in stable disk galaxies.

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REFERENCES

Arp, H. 1966, ApJS, 14, 1
Berger, E., Cowie, L. L., Kulkarni, S. R., Frail, D. A., Aussel, H., & Barger, A. J. 2003, ApJ, 588, 99
Berger, E., Kulkarni, S. R., & Frail, D. A. 2001, ApJ, 560, 652
Bloom, J. S., Kulkarni, S. R., & Djorgovski, S. G. 2002, AJ, 123, 1111
Chapman, S. C., Windhorst, R., Odewahn, S., Yan, H., & Conselice, C. 2003, ApJ, 599, 92
Christensen, L., Hjorth, J., & Gorosabel, J. 2004, A&A, 425, 913
Cohen, J. G., Hogg, D. W., Blandford, R., Cowie, L. L., Hu, E., Songaila, A., Shopbell, P., & Richberg, K. 2000, ApJ, 538, 29
Conselice, C. J., Chapman, S. C., & Windhorst, R. A. 2003, ApJ, 596, L5
Conselice, C. J., et al. 2004, ApJ, 600, L139
———. 2005, ApJ, 633, 29
de Vaucouleurs, G. 1948, Ann. d’Astrophys, 11, 247
Driver, S. P., Windhorst, R. A., & Griffiths, R. E. 1995, ApJ, 453, 48
Ellis, R. S. 1997, ARA&A, 35, 389
Frail, D. A., et al. 2002, ApJ, 565, 829
Freeman, K. C. 1970, ApJ, 160, 811
Fruhter, A. S., & Hook, R. N. 2002, PASP, 114, 144
Hogg, D. W., & Fruhter, A. S. 1999, ApJ, 520, 54
Hubb, E. P. 1926, ApJ, 64, 321
———. 1936, The Realm of the Nebulae (New Haven: Yale Univ. Press)
Johansson, L., & Bergvall, N. 1990, A&AS, 86, 167
Koekemoer, A. M., Fruchter, A. S., Hook, R. N., & Hack, W. 2002, The HST Calibration Workshop: Hubble after the Installation of the ACS and the NICMOS Cooling System, ed. S. Arribas, A. Koekemoer, & B. Whitmore (Baltimore: STScI), 337
Miho, J. C., & Hernquist, L. 1996, ApJ, 464, 641
Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H. 2002, AJ, 124, 266
Price, P. A., et al. 2002, ApJ, 572, L51
Ravindranath, S., et al. 2004, ApJ, 604, L9
Sandage, A. 1961, The Hubble Atlas of Galaxies (Washington: Carnegie Institution)
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Schweizer, F. 1986, Science, 231, 227
Sersic, J. L. 1968, Atlas de Galaxias Australes (Cordoba: Observatorio Astronomico)
Sirianni, M., et al. 2005, PASP, 117, 1049
Soderberg, A. M., et al. 2006, ApJ, 636, 391
Spergel, D. N., et al. 2003, ApJS, 148, 175
Stanek, K. Z., et al. 2003, ApJ, 591, L17
Trujillo, I., et al. 2004, ApJ, 604, 521
———. 2006, ApJ, 650, 18
van den Bergh, S. 2002, PASP, 114, 797
Williams, R. E., et al. 2000, AJ, 120, 2735