The Astrophysical Journal, 642:636–652, 2006 May 10

PROBING COSMIC STAR FORMATION USING LONG GAMMA-RAY BURSTS: NEW CONSTRAINTS FROM THE *SPITZER SPACE TELESCOPE*[1]

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Received 2005 October 19; accepted 2006 January 6

ABSTRACT

We report on IRAC 4.5 μm, IRAC 8.0 μm, and MIPS 24 μm deep observations of 16 gamma-ray burst (GRB) host galaxies performed with the *Spitzer Space Telescope*, and we investigate in the thermal infrared the presence of evolved stellar populations and dust-enshrouded star-forming activity associated with these objects. Our sample is derived from GRBs that were identified with subarcsecond localization between 1997 and 2001, and only a very small fraction ($\sim$20%) of the targeted sources are detected down to $f_{4.5\ \mu\mathrm{m}} \sim 3.5\ \mu$Jy and $f_{24\ \mu\mathrm{m}} \sim 85\ \mu$Jy (3 σ). This likely argues against a population dominated by massive and strongly starbursting (i.e., SFR $\gtrsim 100\ M_\odot\ \mathrm{yr}^{-1}$) galaxies as has been recently suggested from submillimeter/radio and optical studies of similarly selected GRB hosts. Furthermore, we find evidence that some GRBs do not occur in the most infrared luminous regions—hence the most actively star-forming environments—of their host galaxies. Should the GRB hosts be representative of all star-forming galaxies at high redshift, models of infrared galaxy evolution indicate that $\gtrsim$50% of GRB hosts should have $f_{24\ \mu\mathrm{m}} \gtrsim 100\ \mu$Jy. Unless the identification of GRBs prior to 2001 was prone to strong selection effects biasing our sample against dusty galaxies, we infer in this context that the GRBs identified with the current techniques cannot be directly used as unbiased probes of the global and integrated star formation history of the universe.

Subject headings: cosmology: observations — galaxies: high-redshift — galaxies: individual (GRB 970828, GRB 980425, GRB 980613, GRB 980703, GRB 981226, GRB 990705) — infrared: galaxies

1. INTRODUCTION

It is now widely believed that the so-called long gamma-ray bursts (i.e., GRBs with duration $\gtrsim$2 s and soft spectra, as opposed to the short and hard bursts; e.g., Kouveliotou et al. 1993) are intimately connected to the collapse and the cataclysmic destruction of some short-lived and very massive stars. Evidence in this regard includes (1) the signature of Type Ic supernovae and hypernovae in the optical transient emission of GRB counterparts (e.g., Galama et al. 1998; Stanek et al. 2003; Hjorth et al. 2003; Malesani et al. 2004), (2) heavy elements from metal-enriched media typical of supernova remnants observed in the spectrum of several X-ray afterglows (Piro et al. 2000; Reeves et al. 2002), (3) the unquestionable starbursting nature of their host galaxies (e.g., Bloom et al. 1998; Fruchter et al. 1999; Sokolov et al. 2001; Chary et al. 2002; Le Floc'h et al. 2003; Christensen et al. 2004), and (4) the location of GRBs relative to the center of their hosts, which appears to be consistent with a population of progenitors residing in galaxy disks (Bloom et al. 2002). Hence, it has often been proposed that long GRBs could be used as powerful tracers of the global star-forming activity in the early universe (e.g., Wijers et al. 1998; Mirabel et al. 2000; Blain & Natarajan 2000). As illustrated by the recent identification of a burst at $z = 6.29$ (e.g., Kawai et al. 2005), GRBs are indeed detectable up to very high redshifts (Lamb & Reichart 2000). They are also very little affected by dust extinction, which is known to be particularly significant in distant starburst galaxies (e.g., Blain et al. 1999; Franceschini et al. 2001; Chary & Elbaz 2001).

However, this picture relies on the strong assumption that the production of GRBs in a given starburst region scales only with the rate of stars formed in this environment, with no dependence on other physical parameters that may vary from one galaxy to another or that may evolve throughout the lifetime of the universe. This assumption is rather major, as the occurrence of a GRB could strongly depend on the properties of the gas from which its progenitor originates (e.g., metallicity; MacFadyen & Woosley 1999; Ramirez-Ruiz et al. 2002; Heger et al. 2003; Hirschi et al. 2005). It could also vary according to the fraction of those progenitors involved in binary systems (Izzard et al. 2004; Podsiadlowski et al. 2004; Mirabel 2004b), and it finally relies on a nonevolution of the initial mass function with redshift. Testing this "one-to-one" connection between GRBs and star formation is therefore particularly crucial to guarantee an accurate understanding of the use of GRBs as quantitative tracers of galaxy evolution.

One possible approach to investigating this relation is to compare the properties of the hosts of GRBs with respect to the galaxies responsible for the bulk of the star-forming activity in the universe as a function of redshift. It is now well established that a significant fraction of the present-day stellar mass budget was formed during brief and violent infrared-luminous ($L_{\mathrm{IR}} = L_{8-1000\ \mu\mathrm{m}} \gtrsim 10^{11}\ L_\odot$) episodes of star formation within massive ($\mathcal{M} \gtrsim 5\times10^{10}\ M_\odot$) galaxies at $0.5 \lesssim z \lesssim 3$ (e.g., Flores et al. 1999; Blain et al. 2002; Elbaz et al. 2002; Dickinson et al. 2003; Lagache et al. 2003; Franceschini et al. 2003; Le Floc'h et al. 2005; Hammer et al. 2005). Investigating the extinction-corrected star formation rate and the mass of GRB hosts should

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TABLE 1
MID-IR PHOTOMETRY OF GRB HOST GALAXIES

NAME	R.A. (J2000.0)	DECL. (J2000.0)	$f_{4.5\,\mu m}$ [a] (μJy)	$f_{8\,\mu m}$ [a] (μJy)	$f_{24\,\mu m}$ [a] (μJy)	REDSHIFT z	REDSHIFT Reference	L_{IR} [b] ($L_\odot$)	SFR_{IR} [c] ($M_\odot$ yr^{-1})
GRB 970508.......	06 53 49.45	+79 16 19.5	<3.0	<16.5	<83	0.84	1	$<1\times10^{11}$	<17
GRB 970828.......	18 08 31.60	+59 18 51.5	3.7 ± 0.2	<17.8	85 ± 15	0.96	2	$1.4^{+2.5}_{-0.8}\times10^{11}$	24^{+43}_{-14}
GRB 971214.......	11 56 26.40	+65 12 00.5	<3.6	<17.1	<92	3.42	3	$<4.7\times10^{13}$	<8100
GRB 980326.......	08 36 34.28	−18 51 23.9	<3.6	<15.1	<86	...	...	...	...
GRB 980329.......	07 02 38.02	+38 50 44.0	<4.8	<24.4	<97	...	...	...	...
GRB 980425.......	19 35 03.02	−52 50 44.8	2 950 ± 100	11 900 ± 300	27 300 ± 200	0.0085	4	2×10^{9} [d]	0.4
GRB 980519.......	23 22 21.50	+77 15 43.3	<4.2	<24.4	<93	...	...	...	...
GRB 980613.......	10 17 57.82	+71 27 25.5	36.1 ± 1.6	34.9 ± 1.7	170 ± 30	1.10	5	$5^{+9}_{-3}\times10^{11}$	87^{+156}_{-52}
GRB 980703.......	23 59 06.67	+08 35 07.1	11.2 ± 0.6	<23.7	<83	0.97	6	$<1.4\times10^{11}$	<24
GRB 981226.......	23 29 37.21	−23 55 53.8	4.1 ± 0.2	<29.6	<90	...	...	...	...
GRB 990123.......	15 25 30.31	+44 45 59.2	<3.6	<17.1	<82	1.60	7	$<8\times10^{11}$	<140
GRB 990308.......	12 23 11.44	+06 44 05.1	<4.8	<23.7	<87	...	...	...	...
GRB 990506.......	11 54 50,14	−26 40 35.0	1.6 [e]	<23.7	<80	1.31	8	$<4.8\times10^{11}$	<83
GRB 990510.......	13 38 07.11	−80 29 48.2	<4.2	<18.4	<98	1.62	9	$<9.8\times10^{11}$	<170
GRB 990705.......	05 09 54.50	−72 07 53.0	17.2 ± 0.8	<17.8	150 ± 20	0.84	10	$1.8^{+2.1}_{-0.6}\times10^{11}$	32^{+37}_{-11}
GRB 010222.......	14 52 12.55	+43 01 06.3	<3.0	<21.1	<81	1.48	11	$<7.4\times10^{11}$	<130

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[a] All upper limits indicated are 3 σ.
[b] Defined as the energy density integrated between 8 and 1000 μm, and computed assuming a ΛCDM cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, and $\Omega_\lambda = 0.7$.
[c] Assuming SFR_{IR} ($M_\odot$ yr^{-1}) $= 1.72\times10^{-10} L_{IR}$ ($L_\odot$).
[d] More than 75% of the 24 μm monochromatic luminosity of this galaxy originates from a single H II region (see § 4.1). This unusual property makes the extrapolation to the total infrared highly uncertain.
[e] The source is only detected at a $\sim$2 σ level.
REFERENCES.—(1) Bloom et al. 1998; (2) Djorgovski et al. 2001; (3) Kulkarni et al. 1998; (4) Tinney et al. 1998; (5) Djorgovski et al. 2003; (6) Djorgovski et al. 1998; (7) Kulkarni et al. 1999; (8) Bloom et al. 2003; (9) Vreeswijk et al. 2001; (10) Le Floc'h et al. 2002; (11) Jha et al. 2001.

therefore provide tight constraints on the relevance of GRBs for probing the star formation history of the universe.

Previous observational studies on GRB hosts, however, have led to conflicting views about their nature. Based on their properties at optical and near-infrared wavelengths it has been argued that GRB hosts are mostly blue, subluminous, and low-mass galaxies with young stellar populations, characterized by a modest activity of star formation and potential selection effects due to low metallicity (e.g., Sokolov et al. 2001; Le Floc'h et al. 2003; Fynbo et al. 2003; Courty et al. 2004; Prochaska et al. 2004; Christensen et al. 2004). On the other hand, it has also been claimed that the morphology of these objects and their average radio/submillimeter properties rather indicate massive and actively star-forming galaxies (Conselice et al. 2005; Berger et al. 2003). In order to bring tighter constraints on the nature of those sources, we undertook a survey of GRB host galaxies with the *Spitzer Space Telescope*. In this paper we present mid-infrared (mid-IR) images of 16 objects at 4.5, 8, and 24 μm, which allows us to constrain the presence of evolved stellar populations and dust-enshrouded star-forming activity in these sources. In § 2 we describe the *Spitzer* data used in this study. Section 3 outlines general results derived from these mid-IR observations, while the GRB host properties are detailed on a galaxy-by-galaxy basis in § 4. Our findings are discussed in § 5, and they are finally summarized in § 6. Throughout this work, we assume a ΛCDM cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, and $\Omega_\lambda = 0.7$ (Spergel et al. 2003).

2. OBSERVATIONS

2.1. *The Data*

With the exception of the GRB 970228, which was detected in a subluminous blue dwarf galaxy at $z = 0.695$ (Bloom et al. 2001a), our sample of GRB host galaxies was built by considering every GRB identified before 1999 July 10 and localized on the sky with subarscsecond accuracy thanks to the detection of an afterglow at longer wavelengths. This selection is therefore independent of any a priori information on the properties of the hosts (e.g., redshifts, star formation rates, and luminosities). Furthermore, it does not take into account at which wavelength the position of the GRB was determined, i.e., whether the afterglow was optically bright or whether it was only seen in the radio and/or the X-rays (i.e., "dark" burst). This led to a sample of 15 objects, to which we added the host of the burst detected on 2001 February 22 (i.e., GRB 010222). This host galaxy has been claimed to be associated with a SCUBA/MAMBO (Submillimeter Common-User Bolometric Array/Max-Planck Millimeter Bolometer) ultraluminous infrared object (Frail et al. 2002), making it an obvious and quite interesting target for IR observations.

We note, however, that our sample is obviously subject to the various observational cuts that may have biased the identification of GRBs prior to 2001. For instance, most of the bursts considered in this work were detected either with the Wide Field Camera on board the *BeppoSAX* satellite or with the BATSE (Burst and Transient Source Experiment) instrument on board the *Compton Gamma-Ray Observatory*. As revealed by more recent high-energy missions such as *HETE-2* and *Swift*, this may have imposed a first subselection over the whole population of GRBs, depending on their intrinsic luminosity and the hardness of their spectrum. Furthermore, the subsequent ground-based follow-ups that led to the subarcsecond localization of these GRBs, as well as the determination of their redshift from optical spectroscopy, were likely slower than those currently operated by the new networks of more dedicated telescopes. This could in principle

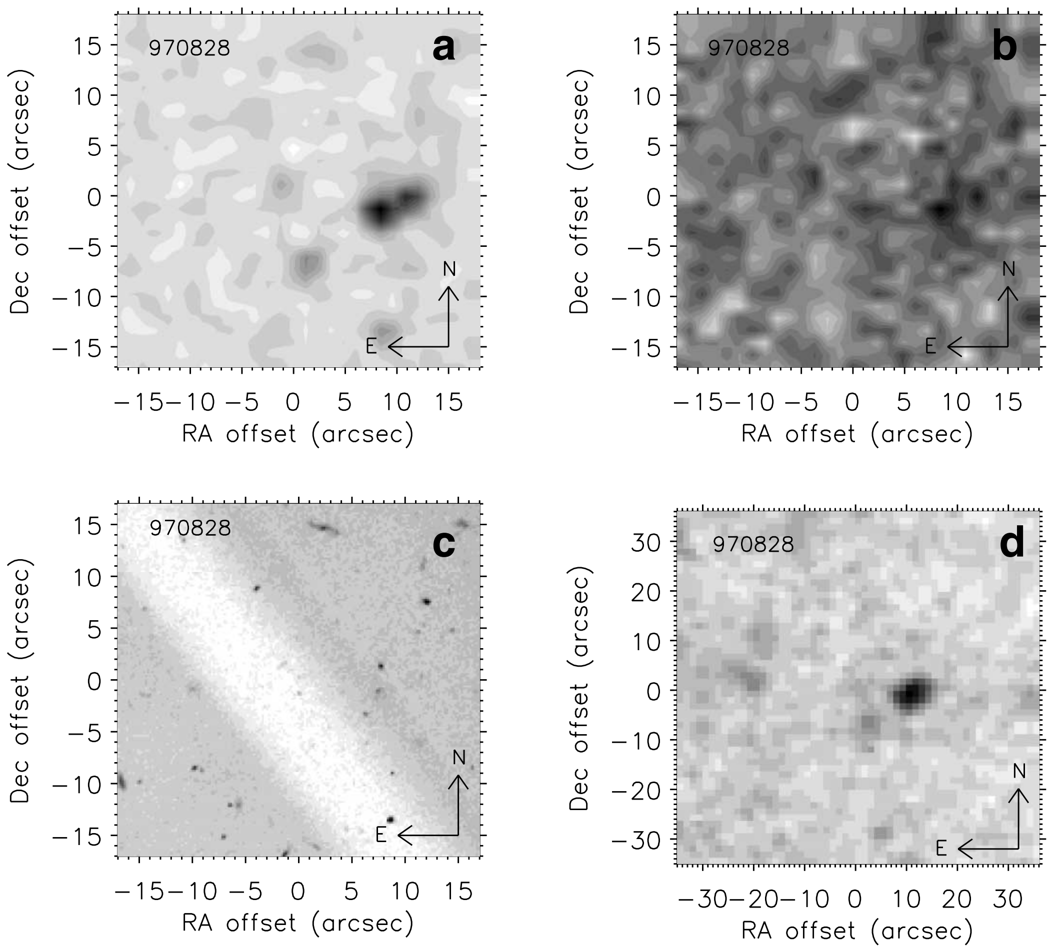

FIG. 1.—Postage stamp mosaic of the area surrounding the GRB 970828 host ($z = 0.96$). The location of the GRB is at the center of each image. (*a*) Image at 4.5 μm, (*b*) image at 8.0 μm, (*c*) optical *HST* image (see text), (*d*) image at 24 μm. North is up and east is to the left.

favor the detection of X-ray and optical transients relatively brighter than the afterglows accompanying the typical bursts now accessible with *Swift* (Berger et al. 2005), thus biasing the selection toward host galaxies with low extinction. In § 5.4 we discuss in more detail the implications of our results, taking into account the above-mentioned issues.

The observations were performed with the *Spitzer Space Telescope* (Werner et al. 2004) as part of the IRS Guaranteed Time Observing program (Houck et al. 2004). The J2000.0 coordinates and the redshifts of the targeted galaxies are reported in Table 1 along with the name of the GRBs that led to their selection. We initiated our *Spitzer* program in 2004, while these GRBs all occurred before 2001 February. The contribution of the emission from their fading afterglow was therefore negligible at the time of our observations.

Each object was imaged with the Infrared Array Camera (IRAC; Fazio et al. 2004) at 4.5 and 8.0 μm, as well as with the Multiband Imager and Photometer for *Spitzer* (MIPS; Rieke et al. 2004) at 24 μm. The IRAC detectors are characterized by 256 $\times$ 256 squared pixel arrays with a pixel size of 1$''$.22, leading to a total field of view of 5$'$.2 $\times$ 5$'$.2. The full width at half-maximum (FWHM) of the point-spread function (PSF) varies between 1$''$.5 and 2$''$ across the different IRAC channels. The MIPS detector at 24 μm uses a 2$''$.45 pixel size array of 128 $\times$ 128 elements, also resulting in a field of view of 5$'$.2 $\times$ 5$'$.2. The image at this wavelength is characterized by a PSF with a FWHM of $\sim$6$''$.

Each observation was performed using a sequence of several frames slightly dithered with respect to the position of the GRB host. Three frames of 100 s were obtained at 4.5 and 8 μm, giving a total integration time of 300 s per source and per band. At 24 μm, 14 frames of 30 s led to a total exposure time of 420 s per source. The data were reduced with standard procedures (i.e., dark current subtraction, cosmic-ray removal, nonlinearity correction, flat-fielding, and mosaicking) using the pipeline of the *Spitzer* Science Center.[9]

The absolute pointing accuracy of the *Spitzer* satellite is better than $\sim$1$''$. The 1 σ relative astrometric uncertainty is less than $\sim$0$''$.3 in the IRAC and MIPS data.

2.2. *IRAC and MIPS Photometry*

With the exception of the GRB 980425 host galaxy lying at $z = 0.0085$ (Galama et al. 1998; Tinney et al. 1998), the other GRB hosts of our sample are all located at cosmological distances ($z \geq 0.84$; see Table 1). Therefore, they are not spatially resolved in the *Spitzer* images, and their fluxes can be estimated using small circular aperture photometry. In the IRAC images, counts were measured over a circled area with a radius of 3 pixels (e.g., 3$''$.6) centered at the position of each target. These counts were translated into flux densities using the conversion factor

[9] See http://ssc.spitzer.caltech.edu/postbcd.

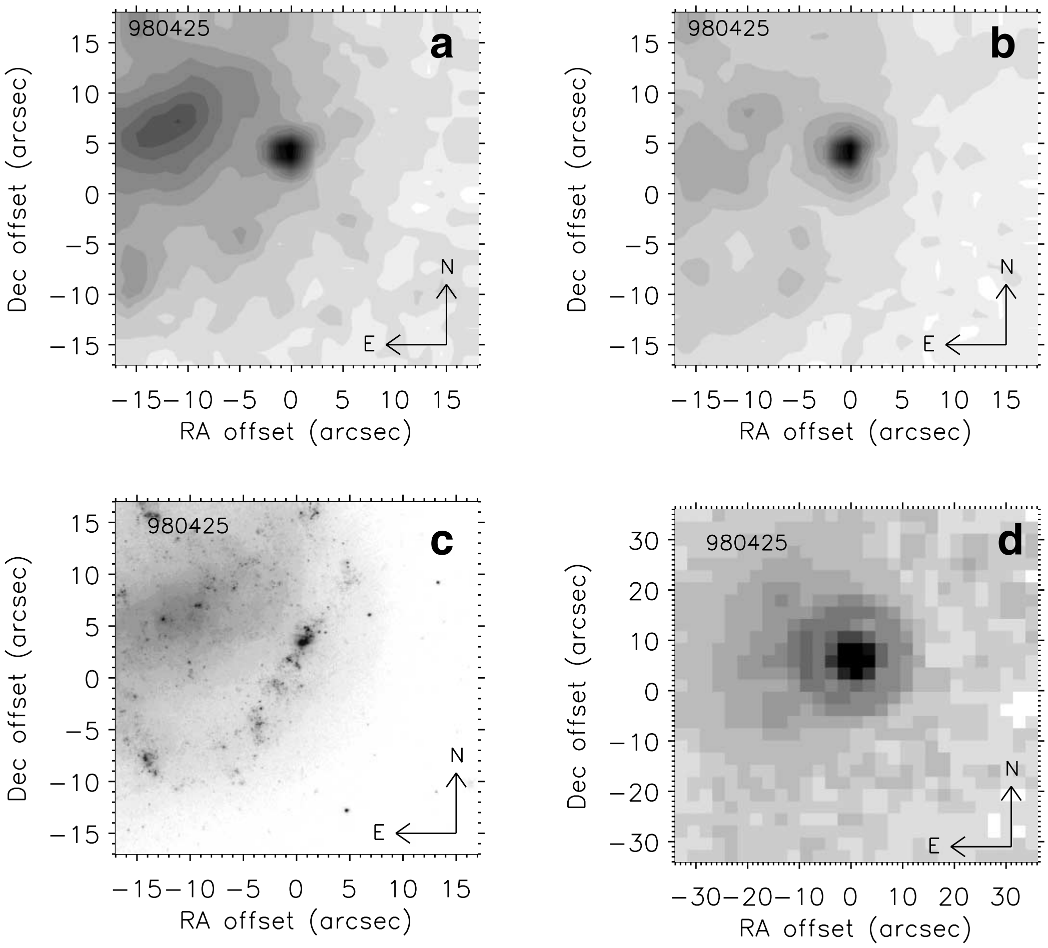

FIG. 2.—Same as Fig. 1, but for the area surrounding the GRB 980425 host at $z = 0.0085$. Note that the bright point source detected at the *Spitzer* wavelengths is not exactly located at the position of the GRB but rather coincides with the H II region detected 6″ away in the northwest direction.

prescribed in the *Spitzer* Observing Manual,[10] and a slight correction was finally applied to account for the extended size of the PSF. Sensitivity limits of ~3.5 and ~20 μJy (3 σ) were estimated at 4.5 and 8.0 μm, respectively, based on the dispersion of the flux measurements obtained over blank-sky regions within the same aperture as that used for the photometry of the objects.

Evidence for nonnegligible blending was found at 24 μm, which is mostly due to the larger size of the PSF and the higher level of extragalactic confusion in the MIPS images than in the IRAC data. To ensure accurate results, source extraction and photometry were therefore performed using the PSF fitting technique of the DAOPHOT software (Stetson 1987). We constructed an empirical PSF from the brightest point sources found in our 24 μm data. This PSF was accordingly scaled to provide the best match to the object detected at the position of the GRB host, thus leading to a direct estimate of its total flux at 24 μm. As a sanity check, the same procedure was also performed using a 24 μm theoretical PSF simulated and provided by the Spitzer Science Center. Within the uncertainties, the photometric measurements that we obtained in this case are consistent with those derived using the empirical PSF. A 3 σ sensitivity limit of ~85 μJy was estimated using aperture photometry.

[10] An electronic version of the *Spitzer* Observing Manual is available at http://ssc.spitzer.caltech.edu/documents/SOM.

Regarding the nearby GRB 980425 host galaxy, a diffuse extended infrared emission was detected up to a distance of 20″–30″ from the center of the object. The sky background level was therefore estimated within an annulus defined by an inner radius of 35″ and a width of 10″. At 4.5 μm the total flux of the galaxy was determined using a 23″ radius aperture. This allowed us to recover most of the extended emission of the object while avoiding the contamination from other field sources located close to the host. At 8 and 24 μm, a 35″ radius aperture was found to provide a very good estimate of the total flux of the galaxy. At these wavelengths the source density in the field is smaller than observed at 4.5 μm, and no other contaminant object was detected within this large aperture.

Our flux measurements and upper limits are given in Table 1. The absolute photometric uncertainties in the IRAC and the MIPS data are less than 5% and 10%, respectively.

3. RESULTS

3.1. *Detection Rate of the GRB Host Galaxies in the IRAC and MIPS Images*

The 4.5 and 8.0 μm IRAC and 24 μm MIPS images of the GRB host galaxies for which a detection in at least one mid-IR band was obtained (see also Table 1) are presented as postage stamps in Figures 1–6. To facilitate the identification of the fields of view, they are displayed along with optical images publicly

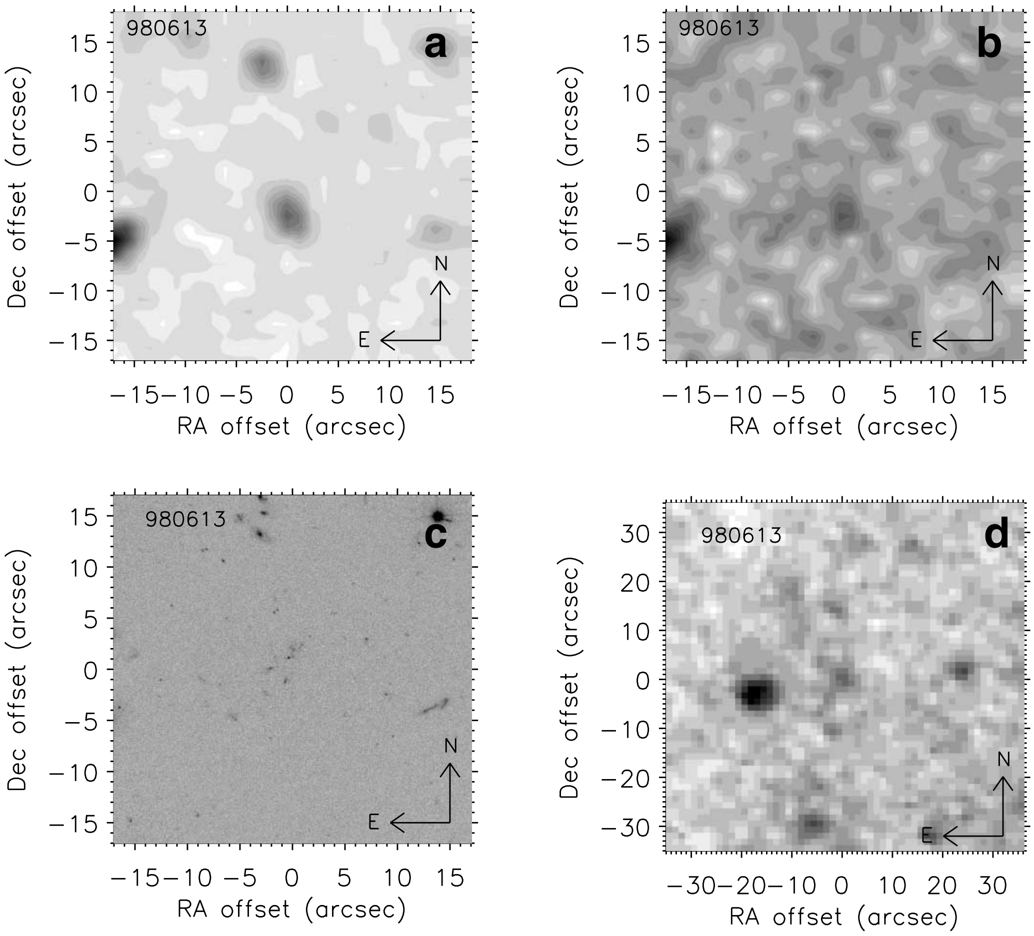

FIG. 3.—Same as Fig. 1, but for the area surrounding the GRB 980613 host at $z = 1.10$.

available in the literature. These optical data were obtained with the Space Telescope Imaging Spectrograph (STIS) or the Wide Field Planetary Camera (WFPC) camera on board the *Hubble Space Telescope* (*HST*) as part of various observing programs led by Fruchter et al. (*HST* Proposals 7966/8189), Holland et al. (*HST* Proposal 8640), and Kulkarni et al. (*HST* Proposal 8867). Most of the reduced images are taken from the Survey of the Host Galaxies of Gamma-Ray Bursts[11] (Holland et al. 2000a), with the exception of the data for the hosts of GRB 970828 and GRB 010222. For the latter, reduced products were provided by the Multimission Archive at the Space Telescope Science Institute (MAST).[12] Most of these *HST* images are displayed with higher spatial resolution in Figure 2 of Bloom et al. (2002).

The nearby host of GRB 980425 is clearly detected in the three bands that we covered with IRAC and MIPS. However, we note that most of the cosmological GRB hosts from our sample *are not detected* with *Spitzer*. Among the 15 high-redshift targeted sources, five are brighter than 3 σ at 4.5 μm, while only one and three objects are detected at 8 and 24 μm, respectively. At $z \sim 1$ a typical L_* galaxy is most often an intermediate-mass IR-luminous spiral (e.g., Zheng et al. 2004; Hammer et al. 2005; Le Floc'h et al. 2005; Melbourne et al. 2005), with a spectral energy distribution (SED) leading to observed flux densities of $f_{4.5\,\mu\mathrm{m}} \sim 10$ μJy, $f_{8\,\mu\mathrm{m}} \sim 8$ μJy, and $f_{24\,\mu\mathrm{m}} \sim 90$ μJy. Given the 3 σ sensitivity limits of our IRAC and MIPS data (see § 2.2), these nondetections consequently have strong implications on the nature of the GRB hosts relative to typical field star-forming galaxies. In § 4 we describe on a case-by-case basis the constraints that can be derived from these results regarding the SEDs of each galaxy. We discuss their global implications for our general understanding of the GRB hosts in § 5.

For each of the three *Spitzer* bands, the nondetected sources were also stacked together in the attempt to infer deeper constraints on the average mid-IR fluxes of these objects considered as a whole population. However, the small number of stacked images improved the original depth of our data by only a factor of ~1.5–3 depending on the wavelength, and no signal was detected above the resulting 3 σ levels. We note that even though we performed the stacking test, this approach should ideally be applied only for sources located in a thin redshift slice, so that the constraint on the flux measured in the stacking can be converted into a more physical quantity associated with these objects. As a result, the broad range of high redshifts covered by our targets (see Table 1) prevents a robust interpretation of our lack of detection in the final stacked GRB host images. It does suggest, however, that considerably deeper observations will be required in order to increase the rate of GRB host detections with *Spitzer*.

3.2. *Infrared Luminosities*

In the local universe, correlations between the mid-IR luminosity and the 8–1000 μm integrated emission of galaxies have

[11] See http://www.ifa.au.dk/~hst/grb_hosts/intro.html.
[12] See http://archive.stsci.edu.

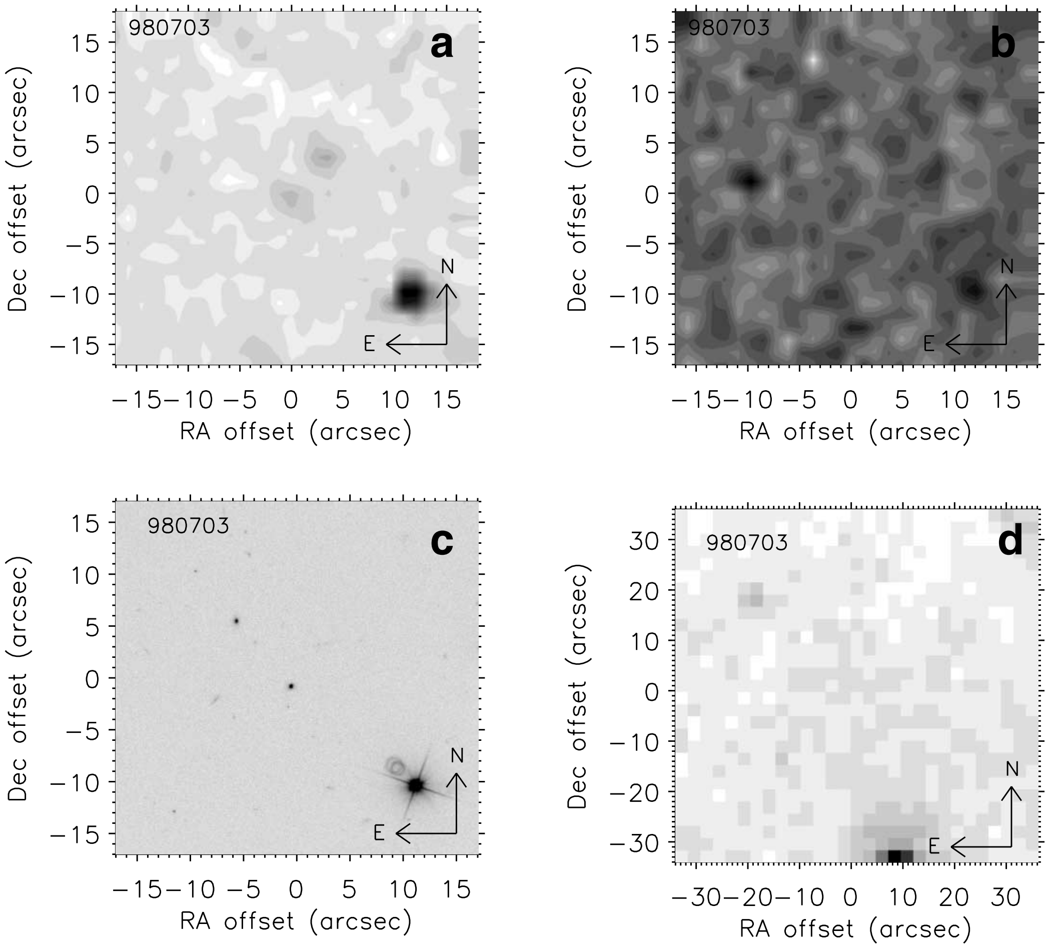

FIG. 4.—Same as Fig. 1, but for the area surrounding the GRB 980703 host at $z = 0.97$.

been observed not only for normal and quiescently star-forming objects (Dale et al. 2001; Roussel et al. 2001) but also for more actively starbursting sources (Chary & Elbaz 2001). Such correlations likely hold also in the distant universe, as the mid-IR/radio relationship resulting from the mid-IR/far-IR and far-IR/radio local correlations is still observed at high redshifts (Gruppioni et al. 2003; Appleton et al. 2004). Therefore, the mid-IR *Spitzer* data could potentially be used to infer some constraints on the total infrared luminosity of distant galaxies.

In this extrapolation, the errors are largely dominated by the uncertainties on the shape of the underlying SED from 8 to 1000 μm. For example, the predictions from the libraries of starburst-dominated SEDs proposed by Chary & Elbaz (2001), Dale et al. (2001), and Lagache et al. (2003) appear to be consistent to within only 0.3 dex up to $z \sim 2$, but this dispersion can be significantly larger assuming other SEDs (e.g., Dale et al. 2005). At $z \gtrsim 1.5$, in fact, our 24 μm data are only sensitive to the brightest galaxies (i.e., ultraluminous infrared galaxies [ULIRGs]), which harbor a large diversity of mid-IR properties (e.g., Armus et al. 2004; L. Armus et al. 2006, in preparation). The prediction of their total IR luminosity based on a single mid-infrared flux measurement can be uncertain by a factor of $\gtrsim$5 for a given object.

To constrain the bolometric luminosity of the GRB host galaxies, we first converted the 24 μm flux density (or upper limit) measured for each object with a known spectroscopic redshift to a monochromatic luminosity at the corresponding rest-frame wavelength 24 μm/$(1 + z)$. Following the approach presented by Le Floc'h et al. (2005), this estimate was then translated into a total IR luminosity using the three libraries mentioned in the previous paragraph. We should emphasize that in these collections of IR spectra, a given monochromatic luminosity at a given wavelength corresponds to a single "total IR" luminosity, thus leading to a unique determination of this quantity for each 24 μm flux measured in our sample. The estimates derived from the three libraries were therefore averaged for each object, and their dispersion was used to quantify the associated uncertainty. We consider our results to be accurate to within a factor of $\sim$2–3 up to $z \sim 1.5$ and within a factor of $\sim$3–5 at higher redshifts. We also keep in mind that such uncertainties apply on a case-by-case basis, and they are obviously smaller when addressing the average IR luminosity of a sample of galaxies.

These estimates are reported in Table 1 along with the equivalent star formation rates (SFRs) derived from these infrared luminosities using the calibration proposed by Kennicutt (1998). These conversions assume that the whole IR emission detected at 24 μm originates from star-forming activity. While the host of GRB 980425 is only a modest infrared emitter ($L_{\rm IR} = 2 \times 10^9\ L_{\odot}$), the three 24 μm–detected high-redshift sources (i.e., the hosts of GRB 970828, GRB 980613, and GRB 990705) are characterized by a total infrared luminosity $L_{\rm IR}$ in the range of $10^{11}\ L_{\odot} \leq L_{\rm IR} \leq 10^{12}\ L_{\odot}$, bringing them to the class of the so-called luminous infrared galaxies (LIRGs; Sanders & Mirabel 1996). However, there is no detection of a host with luminosity larger than $10^{12}\ L_{\odot}$ in the range of the ULIRGs ($10^{12}\ L_{\odot} \leq L_{\rm IR} \leq 10^{13}\ L_{\odot}$) and the

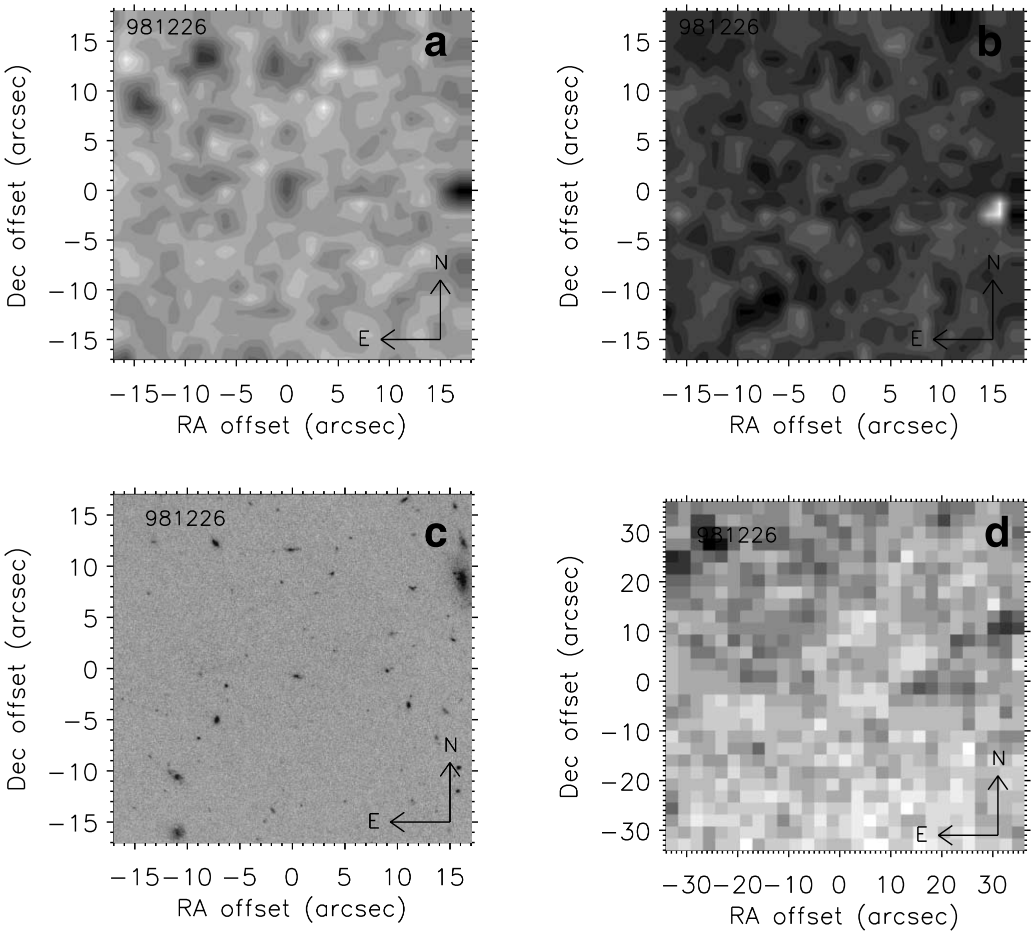

FIG. 5.—Same as Fig. 1, but for the area surrounding the GRB 981226 host.

HyLIRGs (hyperluminous infrared galaxies: $L_{\rm IR} \geq 10^{13}\ L_{\odot}$). In the case of the nondetections, the measured 3 σ sensitivities were used to derive an upper limit on the total IR luminosity when a confirmed redshift was available. Most of these constraints are also consistent with infrared luminosities lower than $10^{12}\ L_{\odot}$, even though we cannot definitely rule out having a few GRB hosts with ULIRG-type IR luminosities given the uncertainties affecting our estimates.

One might note a few potential caveats that could affect these total IR luminosity estimates. First, we cannot completely exclude the presence of a dust-embedded active galactic nucleus (AGN) lurking in these GRB host galaxies and dominating their mid-IR emission. Because the IR SED of AGNs is generally much flatter than the starburst-dominated SEDs that we assumed in the conversion of the 24 μm flux density (see Weedman et al. 2005), our determination of the total IR luminosity could be overestimated by a factor of 5–10 in these cases. However, we consider this possibility unlikely, as no typical AGN signature has ever been reported from the optical, X-ray, and radio properties of these objects.

Furthermore, we have implicitly assumed that the MIPS 24 μm detections purely originate from star-forming activity in the hosts and we have neglected a possible contribution from transient emission due to the effect of the GRB on its close environment. Based on detailed modeling of the heating effect of GRBs and their afterglows on their surrounding region, Venemans & Blain (2001) have argued that a reprocessed dust mid-IR emission could in principle be easily detected by *Spitzer* several years after a burst occurring in a dusty star-forming galaxy. In our analysis of the IR SEDs of the GRB hosts, presented in §§ 4 and 5, we do not consider this likelihood. We argue, however, that the contribution of such a GRB dust emission is unlikely to be significant in our sample.

3.3. *Spectral Energy Distributions*

The GRB host galaxies of our sample have already been extensively observed at optical and near-infrared wavelengths, and some of them have also been targeted by submillimeter and radio observations. Consequently, our *Spitzer* data can be used in a multiwavelength context to derive some constraints on the global SED and the nature of these sources.

We combined our mid-infrared photometry with other broadband imaging data retrieved from the literature (see Fig. 7 legend for references). Optical and near-infrared magnitudes were first corrected from the foreground Galactic extinction using the DIRBE/*IRAS* (Diffuse Infrared Background Experiment/*Infrared Astronomical Satellite*) dust maps of Schlegel et al. (1998) and assuming the $R_V = 3.1$ extinction curve of Cardelli et al. (1989). Depending on the quoted magnitude reference, they were then converted into fluxes using the zero points from the Vega or the AB system. These fluxes, as well as the fluxes or the upper limits gathered at the other wavelengths, were finally converted into rest-frame monochromatic luminosities to provide constraints on the GRB host SEDs from the optical up to the mid-IR or the submillimeter/radio wavelength range.

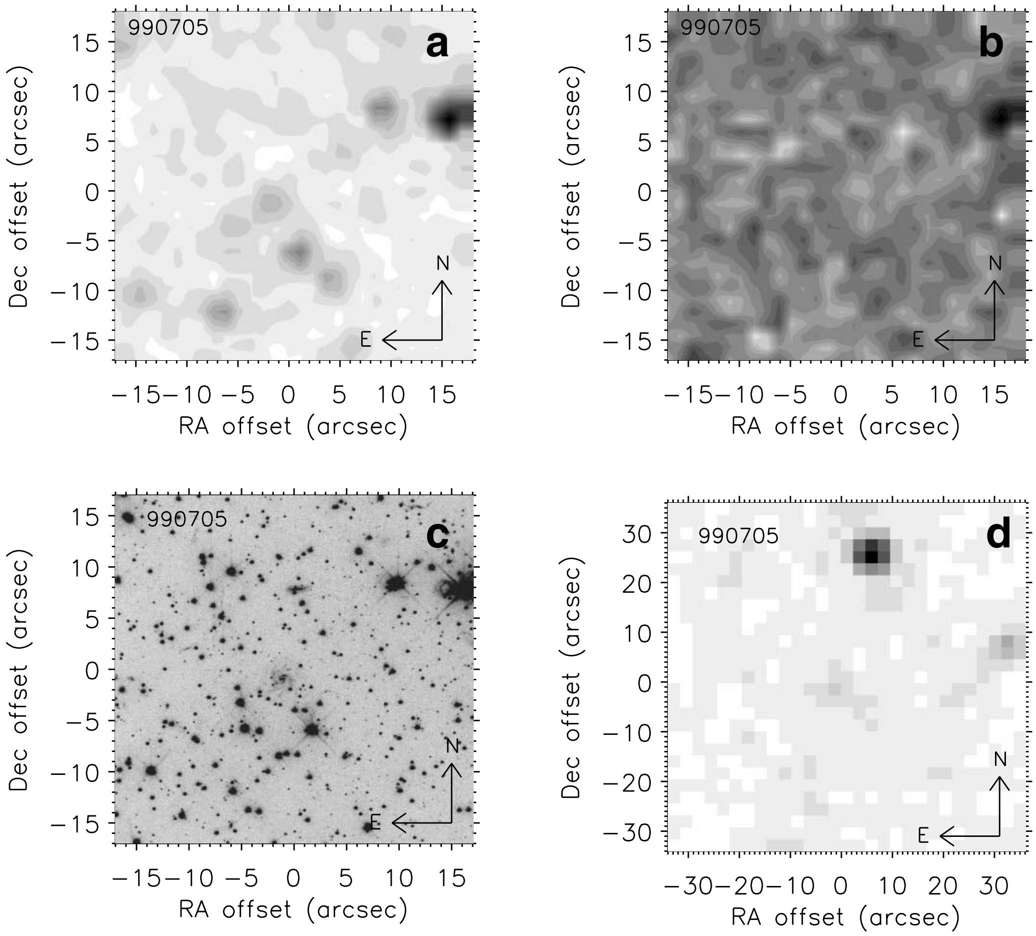

FIG. 6.—Same as Fig. 1, but for the area surrounding the GRB 990705 host at $z = 0.84$.

Our results are illustrated in Figure 7. With the exception of the GRB 990510 host galaxy, which we did not detect with *Spitzer* and which is also optically very faint ($V \sim 28$ mag; Fruchter et al. 2000a), all GRB hosts with a confirmed spectroscopic redshift in our sample are shown. Given the very low rate of detections at long wavelengths (i.e., $\lambda \gtrsim 3\ \mu$m), we do not perform a fit to the current data, and we refer the reader to, e.g., Sokolov et al. (2001), Christensen et al. (2004), and Chary et al. (2002) for a statistical stellar population synthesis of the GRB host optical and near-IR properties. Rather, we consider as a comparison the SED of the prototypical objects NGC 253, M82, and Mrk 231. NGC 253 and M82 are moderately active star-forming spirals characterized by IR luminosities $L_{\rm IR} \sim 1.4 \times 10^{10}$ and $\sim 3.7 \times 10^{10}\ L_{\odot}$, respectively (Förster Schreiber et al. 2003). Their mid-IR SEDs were derived from the *Infrared Space Observatory* (*ISO*) spectra of Förster Schreiber et al. (2003), which were further extrapolated to the UV/optical and the far-IR/radio domains using the modeling provided by Silva et al. (1998). Mrk 231, on the other hand, is a warm ULIRG with an IR luminosity $L_{\rm IR} \sim 4 \times 10^{12}\ L_{\odot}$ powered by both a luminous AGN and a violent starburst (Farrah et al. 2003). Its SED was derived by combining the 5–35 μm spectrum recently obtained by the IRS on board *Spitzer* (Weedman et al. 2005; L. Armus et al. 2006, in preparation) with far-IR and radio data published in the literature (e.g., Ivison et al. 2004). In addition to these three sources, we also displayed the template of a starburst-dominated ULIRG with $L_{\rm IR} = 4 \times 10^{12}\ L_{\odot}$, as well as the SED of a cold LIRG with $L_{\rm IR} = 10^{11}\ L_{\odot}$. These two SEDs were taken from the IR galaxy libraries derived by Chary & Elbaz (2001) and Lagache et al. (2003), respectively.

All these SEDs were chosen to be globally representative of the expected emission from starburst galaxies and IR-luminous sources of the local universe. They are displayed in Figure 7 with the *y*-axis in units of watts per hertz in order to provide a simple and direct qualitative comparison with the observed properties of the GRB hosts as a function of wavelength. As a result they should only be viewed in this context. Since no fitting to the detections and upper limits was attempted, some of these SEDs were actually rescaled to match the luminosity of the GRB hosts at certain wavelengths. This normalization was done in an ad hoc manner, either at the shortest detected wavelengths (e.g., *B* band), in the rest-frame near-IR (e.g., *K* band or IRAC 4.5 μm channel), at the MIPS 24 μm observed wavelength, or even in the radio as in the case of the GRB 980703 host. It better reveals how the global SEDs of the GRB-selected galaxies deviate from the other templates considered in the figure, and it also shows the large diversity of properties characterizing the GRB host population. This is more thoroughly discussed on a galaxy-by-galaxy basis in § 4.

4. THE GRB HOSTS IN A MULTIWAVELENGTH CONTEXT

Following the results derived in § 3.3 we analyze hereafter the multiwavelength properties of the GRB host galaxies using

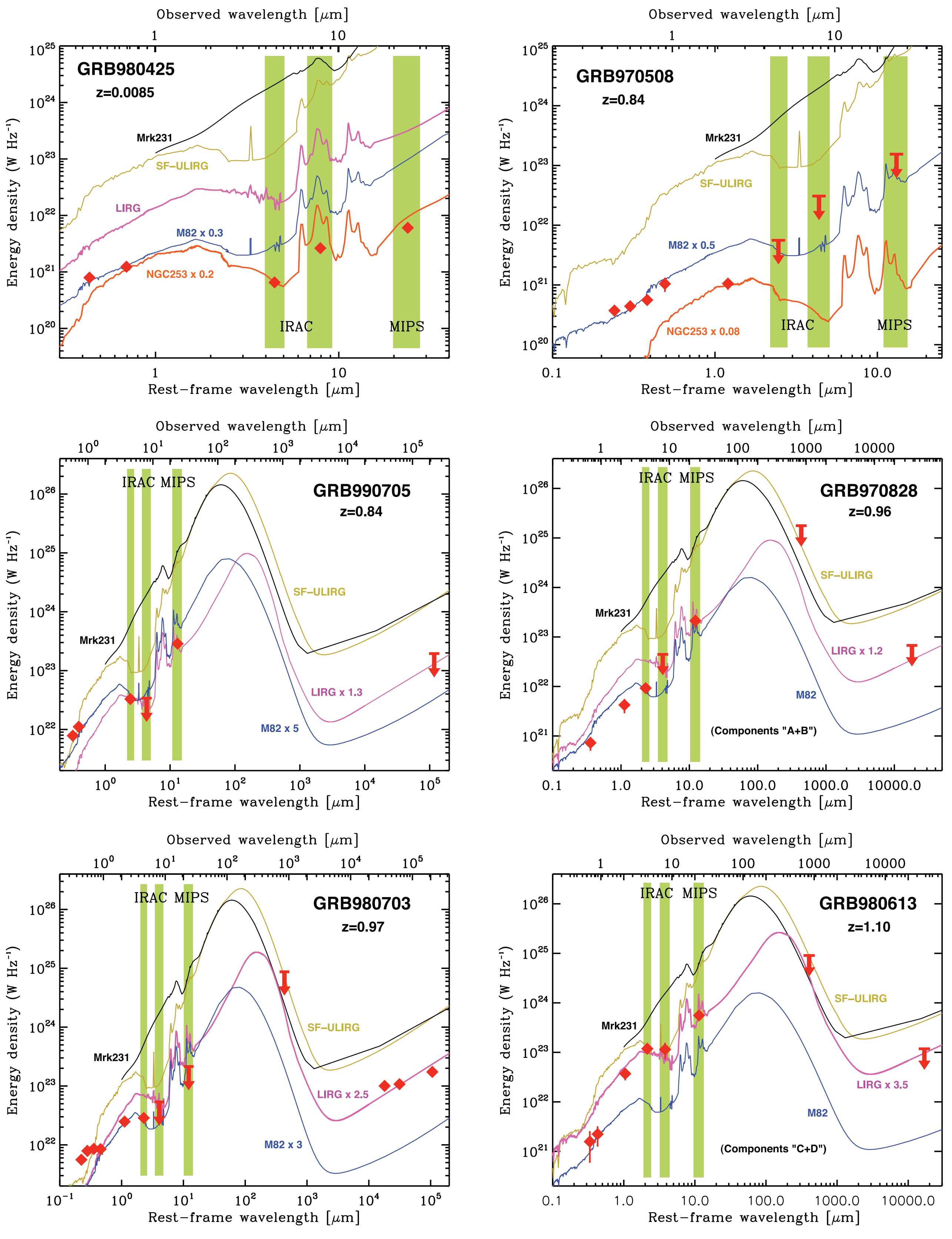

FIG. 7.—Monochromatic luminosities of GRB host galaxies computed from the optical to the radio (*red filled diamonds*; upper limits appear as red downward arrows). Optical, near-IR, submillimeter, and radio photometry measurements are taken from Bloom et al. (1998, 1999), Kulkarni et al. (1998), Fruchter et al. (1999, 2000b), Holland & Hjorth (1999), Vreeswijk et al. (1999), Fynbo et al. (2000), Berger et al. (2001, 2003), Djorgovski et al. (2001, 2003), Holland et al. (2001), Sokolov et al. (2001), Chary et al. (2002), Frail et al. (2002), Le Floc'h et al. (2002, 2003), Barnard et al. (2003), and Tanvir et al. (2004). For comparison we also show the SEDs of NGC 253 (*orange*), M82 (*blue*), and Mrk 231 (*black*), as well as the SED of a starburst-dominated ULIRG with $L_{\rm IR} = 4\times10^{12}\ L_\odot$ (*light brown*, denoted "SF-ULIRG") and the SED of a cold LIRG with $L_{\rm IR} = 10^{11}\ L_\odot$ (*purple*). All these SEDs were corrected for distance, and they are displayed in units of luminosity. As indicated in each panel, a scaling factor was applied to some of them in order to match the observed GRB host photometry at certain wavelengths. The bands where this normalization was performed were chosen on a case-by-case basis to better highlight the differences in luminosity at the other wavelengths (see text for more details). Note that the host of GRB 980613 is a merging system, and the photometry reported in the figure does not refer to the region where the GRB occurred but only to the component detected by *Spitzer* (see § 4.6).

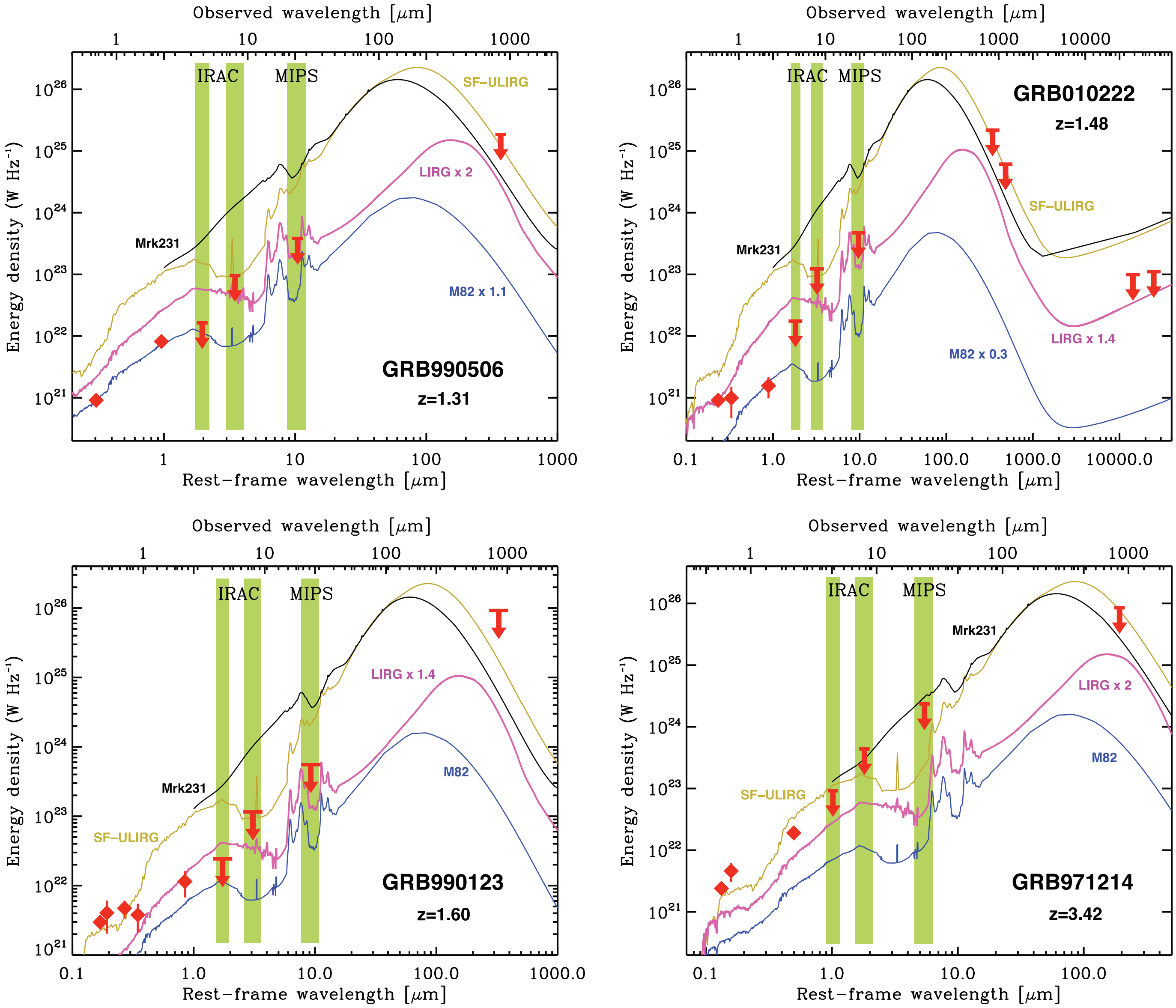

FIG. 7.—*Continued*

the SEDs displayed in Figure 7. We first discuss on a source-by-source basis the objects with a known spectroscopic redshift and ordered by increasing distance from Earth, and we briefly mention the properties of the remaining sources at the end of the section.

4.1. *The Host Galaxy of GRB 980425*

The association of GRB 980425 with SN 1998bw initially proposed by Galama et al. (1998) led to the identification of a nearby subluminous blue galaxy located at $z = 0.0085$. Classified as an Sbc type in the Hubble sequence (Fynbo et al. 2000), it is currently the only GRB-selected object known in the local universe. The supernova SN 1998bw was observed in one of its spiral arms at a distance of ~900 pc from a rather bright H II region.

As shown in Figure 2 this galaxy is detected with a high signal-to-noise ratio in the three *Spitzer* bands. Because of its proximity it is also well resolved, and diffuse emission extending along the major axis is clearly observed. Nonetheless, the most striking result is the detection of a bright mid-IR point source located very close to the region where the GRB occurred. It is the brightest point source detected at 4.5 μm, and its contribution to the total emission of the galaxy is steeply rising with wavelength. With a flux density of 220 and 1815 μJy at 4.5 and 8 μm, it represents 7% and 15%, respectively, of the monochromatic luminosity of the whole galaxy measured in the IRAC channels. At 24 μm its flux reaches ~21 mJy, implying that more than ~75% of the energy radiated by the galaxy at the MIPS wavelength arises from this region.

This luminous point source represents one the reddest objects so far identified in the nearby universe. With a 24 μm monochromatic luminosity $L_{24\,\mu m} \sim 1.1 \times 10^8\, L_\odot$, it is also much more luminous than W49, which is the brightest H II region within the Milky Way (Harper & Low 1971). As a result, its discovery in a GRB-selected galaxy obviously raises the question of a physical link with the hypernova. In spite of the large PSF characterizing the *Spitzer* data, the brightness of this object allowed us to estimate its position along the spiral arm of the galaxy with an accuracy better than 0″.4. We believe that it is unlikely to be related to the close environment of the GRB but rather coincides with the bright H II region located ~5″ (i.e., ~900 pc) in the northwest direction. It could be due, for instance, to a dense super star cluster deeply embedded in dust. This source is to be observed very soon with the Infrared Spectrograph of *Spitzer* to explore in more detail its nature and its mid-IR properties, and the results will be reported in a forthcoming paper.

Should this object indeed be related to intense dusty star formation, our mid-IR observations, as well as the optical view of the galaxy, reveal that the GRB did not occur in the most active site of star formation within its host.

4.2. *The Host Galaxy of GRB 970508*

This object is a blue compact dwarf galaxy (Fruchter et al. 2000b) located at $z = 0.835$ and showing quiescent star formation activity at optical wavelengths (Bloom et al. 1998). Its 4000–8000 Å spectrum reveals a blue continuum with an [O II] emission line corresponding to a star formation rate $\mathrm{SFR}_{[\mathrm{O\,II}]} \sim 1\ M_\odot\ \mathrm{yr}^{-1}$ (not corrected for dust extinction; Bloom et al. 1998). It is detected neither with IRAC nor with MIPS. Given its moderate redshift and the depth of our data, this nondetection with *Spitzer* and the flux density measured in the K band exclude the presence of a massive underlying stellar population in this object. It also argues against a significant contribution from dust-obscured star-forming activity. As a result, the total star formation rate is unlikely to be much larger than the SFR derived from the optical. Based on the sensitivity of our 24 μm data we infer an upper limit of $10^{11}\ L_\odot$ for its total IR luminosity.

Note that the possible association of the GRB 970508 host with a ULIRG proposed by Hanlon et al. (2000) based on ISOPHOT observations is clearly ruled out by the *Spitzer* data.

4.3. *The Host Galaxy of GRB 990705*

GRB 990705 occurred within a large and optically luminous star-forming spiral galaxy observed face-on at $z = 0.8424$ (Le Floc'h et al. 2002). The absolute magnitude of this GRB host corresponds to a $2L_*$ galaxy at $z \sim 1$. While GRBs preferentially occur within subluminous and young sources, the luminosity and the morphology of this object indicate therefore that some bursts can also take place within luminous and more evolved systems.

The galaxy is clearly detected at 4.5 μm with IRAC and at 24 μm with MIPS. Based on the MIPS detection we estimate a total infrared luminosity $L_{\mathrm{IR}} = 1.8^{+2.1}_{-0.6} \times 10^{11}\ L_\odot$ (see Table 1). Hence, this source belongs to the category of the luminous infrared galaxies. Assuming that the totality of the infrared emission is powered by star formation, its luminosity corresponds to a star formation rate $\mathrm{SFR}_{\mathrm{IR}} \sim 32^{+37}_{-11}\ M_\odot\ \mathrm{yr}^{-1}$, which is somewhat larger than the SFR derived from the observed UV continuum ($\mathrm{SFR}_{\mathrm{UV}} \sim 5{-}8\ M_\odot$; Le Floc'h et al. 2002). These characteristics and the observed morphology of the source are actually very similar to those of the IR-luminous spirals that were detected in the *ISO* and *Spitzer* deep surveys (e.g., Flores et al. 1999; Zheng et al. 2004; Bell et al. 2005; Melbourne et al. 2005) and that dominate the star formation at $z \sim 1$ (e.g., Chary & Elbaz 2001; Le Floc'h et al. 2005). Contrary to many other GRB-selected galaxies, the host of GRB 990705 is therefore a very good representative of the sources responsible for the bulk of the star-forming activity in the universe at such redshifts.

As shown in Figure 7, the lack of data from the I, J, H, or K bands results in a rather poor sampling of the SED in the rest-frame optical and near-IR. This prevents us from inferring the exact nature of the emission that dominates the luminosity of this galaxy at these wavelengths. However, the nondetection at 8 μm provides an additional strong constraint that firmly excludes the presence of hot dust dominating at short mid-IR wavelengths. As illustrated by the comparison with the local templates, the IRAC detection at 4.5 μm thus argues for an evolved and massive underlying stellar population dominating the near-IR emission.

4.4. *The Host Galaxy of GRB 970828*

The host of GRB 970828 appears as an early-stage interacting system at $z = 0.96$, with three components (referred to as galaxies "A," "B," and "C") located over a $\sim$30 kpc region (Djorgovski et al. 2001; Bloom et al. 2001b). The galaxy where the burst is believed to have occurred (galaxy B) is faint at optical wavelengths ($R = 25.1$), but it is one of the reddest GRB hosts ($R - K = 3.6$; Djorgovski et al. 2001) in the near-infrared sample studied by Le Floc'h et al. (2003).

There is a clear detection of this merging system at 4.5 and 24 μm. In the IRAC image it appears as a point source roughly centered between galaxies A and B. These two components are only separated by $\sim$1.″9 on the sky (Bloom et al. 2001b). They cannot be resolved with *Spitzer*, and it is not possible to unambiguously determine whether the infrared emission originates from only one or both of these objects.

Based on the MIPS detection we estimate a total infrared luminosity $L_{\mathrm{IR}} = 1.4^{+2.5}_{-0.8} \times 10^{11}\ L_\odot$. This merging system is therefore a LIRG like the host of GRB 990705, characterized by a dust-obscured star formation rate $\mathrm{SFR}_{\mathrm{IR}} \sim 24^{+43}_{-14}\ M_\odot\ \mathrm{yr}^{-1}$. This SFR estimate is much larger than that derived from the UV continuum or from the flux of the [O II] emission line detected in the Keck spectra for galaxies A and B ($\mathrm{SFR}_{\mathrm{UV}} \sim \mathrm{SFR}_{[\mathrm{O\,II}]} \sim 0.5{-}1\ M_\odot\ \mathrm{yr}^{-1}$; Djorgovski et al. 2001). As shown in Figure 7 the spectral energy distribution is steeply rising from the optical to the mid-infrared, which suggests the presence of a typical dust-enshrouded young starburst with no underlying evolved stellar population.

Interestingly enough, GRB 970828 is generally referred to as a typical "dark burst." The optical afterglow of this GRB was not detected despite a deep and prompt search down to $R \sim 24.5$ mag and despite an accurate localization of the event thanks to the detection of its radio transient counterpart. Given the moderately high redshift of its host galaxy, Djorgovski et al. (2001) thus suggested that its optical emission was likely suppressed by an intervening cloud of material within the host, invoking the dust extinction as one possible explanation for the origin of at least a fraction of these "dark GRBs." Our infrared detection with *Spitzer* obviously provides strong support for this hypothesis. In infrared-luminous galaxies, most of the UV radiation emitted by young and massive stars is indeed absorbed by dust and reradiated at longer wavelengths.

4.5. *The Host Galaxy of GRB 980703*

This object is one of the few GRB hosts characterized by an unambiguous detection at radio wavelengths (Berger et al. 2001). Observations performed at the Very Large Array (VLA) after the fading of the GRB radio counterpart revealed at the location of the burst a persistent emission of 68.0 $\pm$ 6.6 μJy at 1.43 GHz. Assuming the far-infrared/radio correlation observed in local starburst galaxies (Condon 1992), Berger et al. (2001) have thus argued that the host of GRB 980703 is an ULIRG (i.e., $L_{\mathrm{IR}} \sim 10^{12}\ L_\odot$) characterized by an SFR of several hundreds of solar masses per year.

At the redshift of this object ($z = 0.97$; Djorgovski et al. 1998), ULIRGs are very easily detected at the mid-IR *Spitzer* wavelengths (i.e., IRAC + MIPS 24 μm). Strikingly, however, the GRB 980703 host galaxy is not detected in our data, except in the IRAC 4.5 μm channel. As shown in Figure 7 its SED from the mid-IR to the radio is therefore not consistent with typical starburst-dominated infrared-luminous galaxies, and our nondetection at 24 μm argues for a very modest star formation rate ($\mathrm{SFR_{IR}} \lesssim 24\ M_\odot\ \mathrm{yr}^{-1}$) when compared to the SFR claimed by Berger et al. (2001).

The excess of radio emission relative to the mid-IR flux can be quantified by the q_{24} parameter defined as $q_{24} = \log(S_{24\ \mu\mathrm{m}}/S_{20\ \mathrm{cm}})$, where S_λ is the observed monochromatic flux density at the considered wavelength (Appleton et al. 2004). Taking into account the sensitivity of our 24 μm data, we derive an upper limit of $q_{24} = 0.09$ for the host of GRB 980703, which is significantly lower than the average value $q_{24} \sim 1$ observed for starburst galaxies (Appleton et al. 2004).

Low q_{24} measurements (i.e., $q_{24} \lesssim 0$) are usually interpreted as the signature of radio-loud objects characterized by an AGN-dominated SED (Higdon et al. 2005). Would the presence of an AGN explain this radio detection in the host of GRB 980703? There is no evidence favoring this hypothesis in the optical spectrum of the host (Djorgovski et al. 1998), and no temporal variability in the radio emission has been reported by Berger et al. (2001). However, we note that the slope of the radio continuum (spectral index $\beta \sim 0.3$, where $F_\nu \propto \nu^{-\beta}$) is significantly flatter than the spectrum characterizing the majority of the starburst "microjansky galaxies" (i.e., $S_{20\ \mathrm{cm}} \lesssim 100\ \mu$Jy) selected at radio wavelengths ($\beta \sim 0.8$; Richards 2000). As a result, the radio spectrum in itself would be more easily explained by the presence of an AGN than supernova remnants in starbursting regions. In fact, the existing data do not allow us to unambiguously disentangle between these two potential contributions, and this GRB host could still be characterized by a rare type of IR-luminous SED yet leading to a faint emission at 24 μm. Deep X-ray observations and/or far-IR MIPS imaging at 70 and 160 μm should provide better constraints on the nature of this object and its spectral energy distribution.

4.6. *The Host Galaxy of GRB 980613*

The host of GRB 980613 is another merging system characterized by a very complex environment with up to nine galaxy fragments interacting with each other at $z = 1.10$ (Chary et al. 2002; Hjorth et al. 2002; Djorgovski et al. 2003). These components show a moderate activity of star formation in the optical (i.e., $\mathrm{SFR_{opt}} \lesssim 5\ M_\odot\ \mathrm{yr}^{-1}$), but some of them display very red $R - K$ colors.

The system is clearly apparent in our *Spitzer* data. In addition to the detections at 4.5 and 24 μm, it is actually the only host galaxy of our sample also detected at 8 μm. The flux estimated at 24 μm corresponds to a total infrared luminosity $L_{\mathrm{IR}} = 5^{+9}_{-3} \times 10^{11}\ L_\odot$, leading to an IR-equivalent star formation rate $\mathrm{SFR_{IR}} \sim 87^{+156}_{-52}\ M_\odot\ \mathrm{yr}^{-1}$.

However, it should be noted that the *Spitzer* detection does not coincide with the component of the interaction where the GRB was observed (component "H"; see Hjorth et al. 2002). It rather corresponds to the very red fragments denoted "C" and "D" by Chary et al. (2002) and Djorgovski et al. (2003). These two components are not spatially resolved by *Spitzer*, but they are located more than 2."5 away from component H and can be distinguished from the latter. We infer that GRB 980613 did not occur in the region harboring the most intense star-forming activity of the system, as was already noted by Hjorth et al. (2002) based on deep optical *HST* data.

The SED of the component detected with *Spitzer* in this interaction presents a striking contrast with the SEDs of the other GRB hosts observed in our data (see Fig. 7). The fluxes measured at 4.5 and 8 μm are particularly bright given the redshift of the host galaxy, and the 8 μm detection reveals a clear inflection of the SED in the rest-frame near-infrared. This suggests not only a significant hot dust emission dominating the SED redward of $\sim$2 μm but also the contribution of an evolved and massive underlying stellar population likely dominating the optical wavelengths.

4.7. *The Host Galaxy of GRB 990506*

GRB 990506 is another typical example of a dark burst undetected in the optical despite deep and prompt imaging after the gamma-ray explosion. Its accurate localization was obtained based on the detection of its radio afterglow (Taylor et al. 2000), and subsequent follow-ups revealed a host galaxy located at $z = 1.31$ (Bloom et al. 2003), characterized by a very compact morphology (Holland et al. 2000b) and a red $R - K$ color ($R - K \sim 4$; Le Floc'h et al. 2003). Its [O II] emission line indicates a dust-uncorrected star formation rate $\mathrm{SFR_{[O\ II]}} = 13\ M_\odot\ \mathrm{yr}^{-1}$ (Bloom et al. 2003), which is substantially higher than the median SFR characterizing the global population of the GRB host galaxies at optical wavelengths.

It is marginally detected at the 2 σ level at 4.5 μm, but it is not seen in the 8 and 24 μm images. As already suggested by Barnard et al. (2003), who did not detect this object with SCUBA, this case reveals that dark GRBs are not systematically associated with dust-enshrouded massive star-forming activity.

4.8. *The Host Galaxy of GRB 010222*

GRB 010222 has been widely referred to as the prototypical burst associated with violent starburst activity at high redshift, also bringing further support for the death of young and massive stars as the origin of long GRBs. A persistent source with an average flux density of 3.74 ± 0.53 mJy at 850 μm and $1.05\ 0 \pm 0.22$ mJy at 1.2 mm was indeed observed with SCUBA and MAMBO at the location of its afterglow (Frail et al. 2002). At the redshift of the burst ($z = 1.48$; Jha et al. 2001), the reported flux densities correspond to an infrared luminosity $L_{\mathrm{IR}} \sim 4 \times 10^{12}\ L_\odot$ assuming typical far-infrared galaxy SEDs. Therefore, Frail et al. (2002) argued that the GRB 010222 host is a dusty ULIRG experiencing a very intense episode of star formation ($\mathrm{SFR} \sim 600\ M_\odot\ \mathrm{yr}^{-1}$).

However, this object is not detected in our data (see Fig. 8), which obviously raises some doubt regarding its association with the SCUBA/MAMBO source. The typical SCUBA and MAMBO galaxies have easily been detected with *Spitzer* (Charmandaris et al. 2004; Egami et al. 2004; Frayer et al. 2004; Ivison et al. 2004), while they are located on average at higher redshifts than the host of GRB 010222 (e.g., Chapman et al. 2003). Furthermore, this GRB host galaxy is a very faint blue object that contrasts with the typical properties characterizing the optical counterparts of the SCUBA sources (Smail et al. 2004). Considering that it is not detected with more than 3 σ in any of the *Spitzer* mid-IR bands or at radio wavelengths (Berger et al. 2003), the claim for an association between the GRB host and the SCUBA/MAMBO source thus appears questionable. In fact, Frail et al. (2002) mention the presence of four other redder galaxies detected in the K band and located within the 15" diameter beam of SCUBA centered at the position of the GRB host. Three of these galaxies *are* detected with IRAC and with MIPS, which could suggest that the SCUBA/MAMBO detection is likely associated with one or several of these other sources instead.

Strictly speaking, however, the nondetection of the host at 24 μm is not sufficient to completely rule out the possible association between GRB 010222 and a ULIRG. The SED of ULIRGs can be characterized by a strong silicate absorption at 9.7 μm rest frame (Spoon et al. 2004; Armus et al. 2004). At the distance of the host ($z = 1.48$), this feature would be redshifted in the

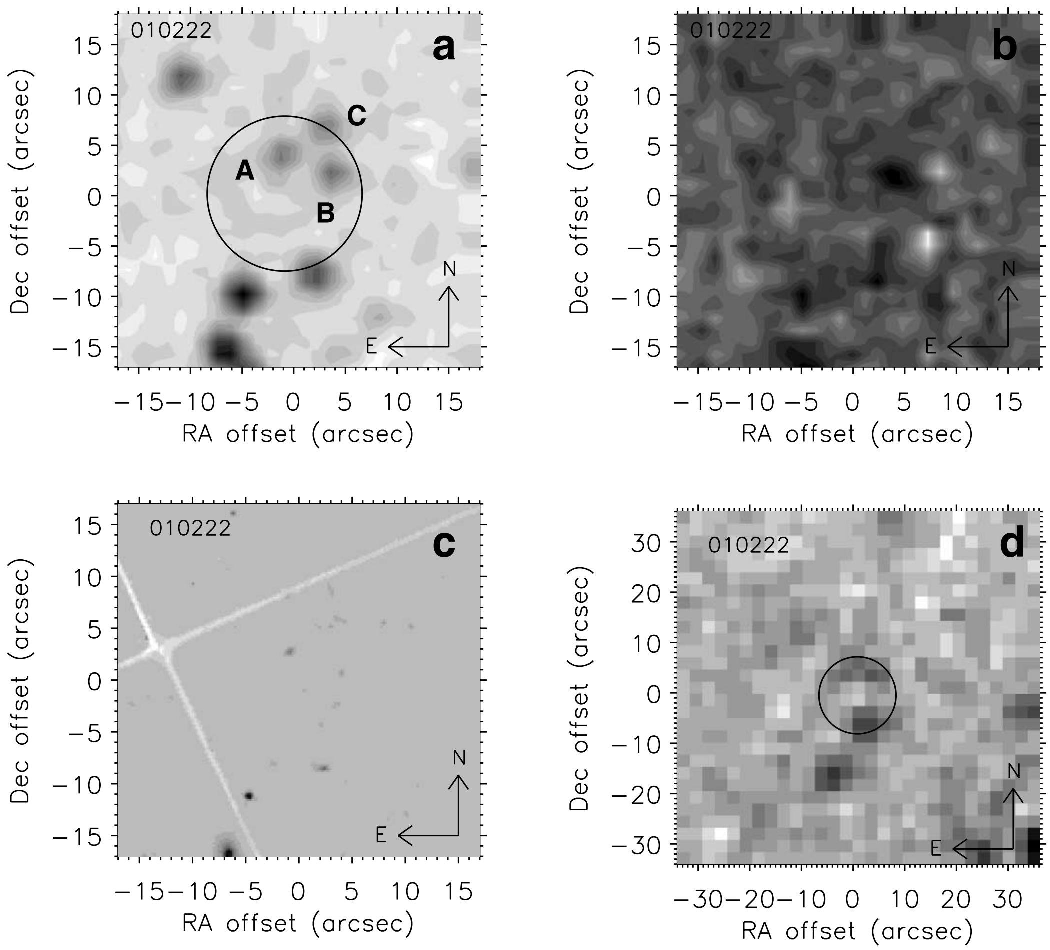

FIG. 8.—Same as Fig. 1, but for the area surrounding the GRB 010222 host galaxy at $z = 1.48$. The 15″ diameter beam of SCUBA centered on the host is displayed in the IRAC 4.5 μm and MIPS 24 μm images. In (*a*), we also indicate the three sources referred to as galaxies A, B, and C by Frail et al. (2002).

24 μm band, which could explain the nondetection by MIPS at this wavelength (see Kasliwal et al. 2005 for a detailed discussion on this issue). In this case, however, the nondetection at 4.5 μm would still remain very puzzling.

4.9. *The Host Galaxy of GRB 990123*

The high spatial resolution image of this galaxy obtained with the *HST* revealed a strongly interacting system with a complex morphology, and the optical transient of GRB 990123 was actually observed very near a star-forming region associated with one of its merging components (Bloom et al. 1999; Fruchter et al. 1999; Holland & Hjorth 1999). Located at $z = 1.6$ (Kulkarni et al. 1999), the GRB host has a luminosity of $\sim 0.5L_*$ in the optical, and its observed UV continuum argues for a small amount of star formation (SFR $\sim 4\ M_\odot\ \mathrm{yr}^{-1}$; Bloom et al. 1999).

Our IRAC and MIPS observations did not lead to any detection in the infrared, which indicates that this subluminous galaxy is a low-mass quiescent starburst with no significant contribution from dust-enshrouded star-forming activity.

4.10. *The Host Galaxy of GRB 990510*

This host galaxy is a very faint object ($V \sim 28$ mag; Fruchter et al. 2000a) at $z = 1.62$ (Vreeswijk et al. 2001) with an absolute *B*-band magnitude $M_B \sim -17.20$ mag (Le Floc'h et al. 2003). We did not detect it with IRAC or with MIPS. This suggests that the faintness of this source observed in the optical does not originate from a high amount of dust extinction but rather points to an intrinsically low-mass and young object with a negligible amount of star formation.

4.11. *The Host Galaxy of GRB 971214*

The host of GRB 971214 is one of the most distant objects that have been spectroscopically identified based on the optical transient of a GRB. Located at a redshift $z = 3.418$, it is an $\sim L_*$ galaxy with a somewhat irregular morphology and a surface brightness probably dominated by an exponential profile (Kulkarni et al. 1998; Odewahn et al. 1998). Neglecting possible extinction by dust, its UV continuum and Lyα emission line both argue for a rather small star formation rate (SFR $\sim$ 1–5 $M_\odot\ \mathrm{yr}^{-1}$; Kulkarni et al. 1998).

We did not detect this galaxy with *Spitzer*. At the redshift of the GRB, our 24 μm data are only sensitive to HyLIRGs ($L_{\mathrm{IR}} \geq 10^{13}\ L_\odot$) at the flux limit of our observations. Therefore, the nondetection by MIPS does not put a strong constraint on the infrared properties of the host. At similar redshifts, however, typical Lyman break galaxies (LBGs) are easily detected at the short IRAC wavelengths, and some of them are also detected at 24 μm (Barmby et al. 2004; Huang et al. 2005). Hence, this lack of detection in our data indicates that the host of GRB 971214 is likely not as massive and evolved as the LBGs coexisting at the same epoch. Neither is it one of the most actively starbursting LBGs.

4.12. *The Host Galaxies of GRB 980326, GRB 980329, GRB 980519, and GRB 990308*

The redshifts of these four GRB host galaxies have not been determined spectroscopically. Deep observations performed with the *HST* have shown that they are very faint in the optical ($R \gtrsim 26$ mag; Jaunsen et al. 2003; Fruchter et al. 2001), and none of them are actually detected with *Spitzer*. This suggests that their faint optical emission is probably not due to a large extinction by dust but rather indicates galaxies with very low bolometric luminosities. In favor of this interpretation, we note that the very faint host galaxy of GRB 990510 ($V \sim 28$ mag, $z = 1.62$) was not detected in our sample either in spite of its redshift being easily accessible for *Spitzer* (see § 4.10). The possibility that these objects are at very high redshift cannot be excluded, however (see, e.g., Fruchter 1999), in which case the nondetections with IRAC and MIPS would not be surprising.

4.13. *The Host Galaxy of GRB 981226*

As in the case of the four sources previously discussed, the spectroscopic redshift of the GRB 981226 host has not been established. However, it is brighter in the optical ($R \sim 24.5$; Frail et al. 1999; Holland et al. 2000c; Saracco et al. 2001). It has been detected in the K_s band ($K_s = 21.1 \pm 0.2$; Le Floc'h et al. 2003), and it is also clearly apparent in the IRAC 4.5 μm image. Its $R - K$ color makes it one of the reddest GRB host galaxies that have been studied so far, and its SED also looks rather steep between the K_s band and the IRAC 4.5 μm channel.

Our current data set does not allow us to distinguish whether the IRAC detection and the red colors of this host reveal an old star population, hot dust emission, or a combination of both. Invoking the presence of dust may be attractive, since GRB 981226 is also one of the few dark bursts that did not exhibit any detectable optical counterpart. However, we consider this explanation unlikely, as this object is not detected at 8.0 or 24 μm. Note that neither was it detected in the submillimeter ($F_{850\,\mu\mathrm{m}} = -2.79 \pm 1.17$ mJy; Barnard et al. 2003), and the flux reported by Berger et al. (2003) at radio wavelengths points to less than a 2 σ detection ($F_{8.46\,\mathrm{GHz}} = 21 \pm 12$ μJy). The interpretation is further complicated by the fact that no spectroscopic redshift has ever been determined for this galaxy.

5. DISCUSSION

5.1. *The Origin of the Infrared Emission in the GRB Host Galaxies*

The IRAC and MIPS instruments on board *Spitzer* have recently opened new exciting perspectives for tackling the evolution of galaxies in the early universe. With unprecedented sensitivity at 3.6–8.0 μm, the IRAC channels can sample the rest-frame near-IR emission of very distant sources, while the MIPS imager can detect the hot dust emission of active starbursts and AGNs up to $z \sim 2$–3. Both cameras therefore provide new insights for studying the evolved stellar populations and the importance of dust-obscured star formation at high redshift.

Interpreting the observed mid-IR emission of GRB-selected galaxies can, however, be more subtle than analyzing the other mid-IR sources detected in the field. As mentioned in § 3.2 Venemans & Blain (2001) have argued that optical and UV afterglows can be significantly absorbed by dusty material surrounding GRBs and that the reprocessed IR light can be observed several years after a burst because of the very long timescale variations of the heated dust emission. The SED of this dust component would be characterized by a steep increase from the short wavelengths up to ~8–10 μm rest frame, followed by a gentle decline in the mid-IR and far-IR (see Fig. 5 of Venemans & Blain 2001). Up to redshift $z \sim 1$–2, it could dominate the total luminosity of the host galaxy, which would call into question the use of the IRAC and MIPS flux measurements as mass and star formation rate indicators.

However, we did not find any obvious evidence for such "GRB-heated" dust emission among the *Spitzer*-detected GRB hosts. In the resolved GRB 980425 host galaxy at $z = 0.0085$ we do not see any signature of this effect at the location of the hypernova SN 1998bw, while the infrared emission detected in the complex environment of the host of GRB 980613 ($z = 1.10$) does not coincide with the galaxy fragment where the burst occurred. At the redshift of the other sources (i.e., $0.84 \leq z \leq 1.1$), the IRAC 8 μm and MIPS 24 μm bands constrain the rest-frame 4 μm/12 μm flux ratios, which appear to be too red compared to the SED of the GRB dust component predicted by the models.

The detectability of this GRB dust emission obviously depends on the efficiency of the absorption of the UV/optical afterglow. As already noted by Venemans & Blain (2001), it should be preferentially observed toward the host galaxies of those dark bursts originating from dust-enshrouded star-forming regions.[13] Even though three of our galaxies indeed fall in this category (i.e., the hosts of GRB 970828, GRB 981226, and GRB 990506), our sample has mostly been built from GRBs pinpointed with optical afterglows, and our selection could also induce a bias against the detection of this burst-remnant dust emission.

As a result, we conclude that the contribution of this component is negligible in our data. The IRAC and MIPS detections should truly reflect the properties of the stellar populations and the global star-forming activity within the observed host galaxies.

5.2. *A Panchromatic View on the Nature of the GRB Hosts*

A few sources from our sample display clear signatures of evolved stellar populations and intense starbursting activity. An example is the host of GRB 990705 at $z = 0.84$, which harbors active star formation (SFR$_{\mathrm{IR}} \sim 32$ $M_\odot$ yr^{-1}; see § 4.3) and appears as a large and massive Sc spiral galaxy typical of the disk-dominated systems at these redshifts. Other cases of active starbursts, such as the host of GRB 000418, have previously been found at radio and submillimeter wavelengths (Berger et al. 2003).

On average, however, our MIPS observations combined with the submillimeter and radio published photometry do not really favor a population of GRB host galaxies dominated by very active and luminous dusty starbursts. With the exception of the host of GRB 980703, which we discussed in § 4.5, our 24 μm nondetections are consistent with the existing SCUBA and VLA data, and they are even more constraining if one assumes typical IR-luminous and starburst-dominated SEDs for the hosts of GRBs (see Fig. 7). Our measurements argue against the presence of numerous LIRGs and ULIRGs in the GRB host population, and they also point to lower star formation rates (see § 3.2 and Table 1), which are not consistent with some conclusions obtained by other groups. For instance, Berger et al. (2003) have recently claimed that 20% of GRB host galaxies have SFR ~ 500 $M_\odot$ yr^{-1}, which is obviously in disagreement with our *Spitzer* results.

Similarly, our IRAC data argue very clearly against a population of sources with massive and evolved stellar populations dominating their near-IR rest-frame emission. Assuming a standard conversion between the mass and the rest-frame near-IR absolute

[13] The so-called dark bursts can also be GRBs with intrinsically faint afterglows (e.g., Fox et al. 2003) or very high redshift bursts with optical counterparts suppressed by Lyα absorption (e.g., Lamb & Reichart 2000).

luminosity [i.e., $-0.25 \lesssim \log(\mathcal{M}/L_K) \lesssim +0.15$; Bell et al. 2003], the fluxes or upper limits that we measure at 4.5 μm translate for most cases into masses $\mathcal{M} \lesssim 5 \times 10^9\ M_\odot$. The IRAC data are also consistent with the constraints derived from the optical and the near-IR published photometry assuming typical SEDs of blue star-forming galaxies (see Fig. 7), and our results globally agree with the rather small masses determined by Chary et al. (2002) using deep *K*-band observations of GRB hosts at Keck. Our interpretation, on the other hand, strikingly contrasts with the conclusions recently obtained by Conselice et al. (2005), who argue for a trend toward massive sources at $z \gtrsim 1$ based on an analysis of the GRB host morphologies.

Hence, the *Spitzer* view on the GRB-selected galaxies rather suggests low-mass sources characterized by a relatively modest amount of dust obscuration. Similar conclusions have already been derived based on the optical and near-IR properties of these objects (e.g., Le Floc'h et al. 2003; Courty et al. 2004; Christensen et al. 2004).

5.3. *Implications for GRBs as SFR Probes*

Because of their dust-penetrating power and their relation to the death of young and massive stars, it has been argued that the long GRBs could be used as an unbiased probe of the star formation history of the universe. From a purely statistical point of view, their host galaxies should therefore be representative of the sources producing the bulk of the stellar mass at high redshift. Are our results consistent with this picture?

The detection of the cosmic infrared background and the recent surveys performed at infrared/submillimeter/radio wavelengths have revealed that a significant fraction of the present-day stellar mass was formed in the past during short-lived and dust-obscured episodes of intense star formation within infrared-luminous galaxies (e.g., Puget et al. 1996; Blain et al. 1999; Chary & Elbaz 2001; Cowie et al. 2004). At $z \sim 1$, these infrared-luminous starbursts (i.e., $L_{\rm IR} \geq 10^{11}\ L_\odot$) are responsible for $\sim$70% of the star-forming activity in the universe (Le Floc'h et al. 2005), and their contribution is believed to be even more important at higher redshifts (e.g., Blain et al. 2002; Lagache et al. 2003). Using *Spitzer*-updated IR galaxy evolution models (e.g., Lagache et al. 2004; Chary et al. 2004) we estimate that more than half of the global star-forming activity throughout the lifetime of the universe has occurred within galaxies characterized by $f_{24\,\mu\rm m} \gtrsim 100\ \mu$Jy. In this context, the significant fraction of nondetections in our MIPS data is therefore surprising.

Similarly, the downsizing evolution of the cosmic star formation history reveals that the bulk of the star-forming activity has been moving from massive galaxies at high redshifts to low-mass objects in the present-day universe (e.g., Cowie et al. 1996; Juneau et al. 2005). Should the long GRBs trace the whole population of distant starbursting sources, we would therefore detect these bursts preferentially toward massive systems easily accessible to IRAC.

This apparent discrepancy between the nature of the GRB host galaxies as a whole and the sources dominating the high-redshift star-forming activity has already been noted from a comparison between their colors and luminosities at optical and near-IR wavelengths (e.g., Le Floc'h et al. 2003) or their SFR recovered from cosmological simulations (Courty et al. 2004). For instance, GRB hosts appear blue and optically subluminous compared to the massive dusty starbursts. Very often they also display Hδ in emission (Djorgovski et al. 1998; Soderberg et al. 2004; Prochaska et al. 2004; Gorosabel et al. 2005), which reveals star formation episodes characterized by younger populations than those typically observed in the distant infrared-luminous galaxies (Flores et al. 1999; Hammer et al. 2001, 2005). As a result we conclude that the GRB afterglows, as they are currently selected, cannot be considered to be unbiased probes of the integrated activity of star formation in the high-redshift universe.

5.4. *A Bias in the Spitzer Sample?*

As we have already described in more detail, our sample consists mostly of galaxies pinpointed using optical afterglows identified prior to 2001, when GRB follow-ups were not as prompt and efficient as they are currently. This could bias the selection toward the most luminous transients and therefore against dust-enshrouded GRBs occurring within infrared-luminous galaxies. A relevant case illustrating this hypothesis is given by the dark burst GRB 970828 and its host galaxy (see § 4.4). The accurate coordinates of this GRB were determined thanks to the detection of its radio afterglow, and the absence of optical transient emission was interpreted as an evidence for dust extinction in the host galaxy (Djorgovski et al. 2001). The detection of this object at 24 μm clearly supports this interpretation, and it suggests that a sample of GRB hosts purely selected with optical afterglows could be biased toward dust-free sources. In this context, the X-Ray Telescope (XRT) instrument on board the recently launched *Swift* satellite is now routinely localizing X-ray GRB afterglows with an accuracy of $\sim$5″ on the sky. In the near future, the comparison between the properties of GRB host galaxies selected from optical and X-ray afterglows will provide better insight into this possible bias affecting our current sample.

On the other hand, we have not detected the two other host galaxies selected from radio afterglows with no optical transient (i.e., the hosts of GRB 981226 and GRB 990506), which shows that not all dark GRBs originate from dusty galaxies. A similar conclusion was reached by Barnard et al. (2003) based on the nondetection of four dark GRB hosts with the SCUBA camera at 850 μm. In fact, many of these dark bursts could simply be associated with intrinsically very faint and/or fast-decaying optical afterglows (e.g., Fynbo et al. 2001; Fox et al. 2003).

In addition to this observational bias that could affect our selection, another explanation might be directly related to the physical properties characterizing the local environments where long GRBs take place. Based on theoretical simulations and the connection between GRBs, hypernovae, and Type Ic supernovae, it has been argued that long GRBs should more likely occur within binary systems (Izzard et al. 2004; Podsiadlowski et al. 2004; Mirabel 2004a, 2004b), whose frequency in star-forming regions may vary with redshift. Furthermore, it has been suggested that long gamma-ray bursts would be more efficiently produced—and they would also appear more luminous—if they originate from low-metallicity progenitors (e.g., MacFadyen & Woosley 1999; Ramirez-Ruiz et al. 2002; Meynet & Maeder 2005; Hirschi et al. 2005). Massive stars with metal-poor envelopes keep a high angular momentum in the latest stage of their evolution, and they are also less subject to mass loss. After the final collapse, this would favor the formation of a fast-rotating black hole with accretion of material that could more easily lead to a bright GRB event. In this case GRBs would be preferentially observed in young and chemically unevolved galaxies, which would explain this lack of massive and dusty starbursts in our *Spitzer* data.

In fact, direct evidence for low metallicity has already been observed in several GRB host galaxies (Soderberg et al. 2004; Prochaska et al. 2004; Gorosabel et al. 2005). Furthermore, the global properties of these objects, such as their blue colors, their relatively low luminosities, their Lyα emission, and their high *specific* star formation rate (Le Floc'h et al. 2003; Fynbo et al. 2003; Christensen et al. 2004), do support a picture in which

GRBs occur in low-mass, young, and hence metal-poor starbursts. This is also corroborated by the cosmological simulations obtained by Courty et al. (2004), who identify the GRB hosts as the most efficient star-forming objects (i.e., sources with the highest specific SFR) and not as galaxies with obvious high SFR. In fact, a good illustration of this global property can be given by the complex environment of the host of GRB 980613. This burst did not occur in the region detected by MIPS and harboring therefore the most intense star-forming activity within the galaxy (see also Hjorth et al. 2002 for a similar conclusion based on optical *HST* data). Note that the same interpretation can be derived from the characteristics of the GRB 980425 host galaxy, since the hypernova SN 1998bw did not occur in the most active region as revealed by the very luminous mid-IR point source detected with *Spitzer*.

6. SUMMARY

We have presented 4.5 and 8.0 μm IRAC and 24 μm MIPS observations of 16 GRB host galaxies, and our results can be summarized as follows:

1. It is now well established that long GRBs are markers of recent bursts of star formation in galaxies. However, most of the GRB hosts in our sample were not detected in the rest-frame near-IR and mid-IR with *Spitzer*, which argues against a population of sources globally dominated by massive and IR-luminous starbursts ($L_{\rm IR} \gtrsim 5 \times 10^{11}\ L_\odot$). Current IR galaxy evolution models indicate that more than half of the integrated star-forming activity throughout the lifetime of the universe occurred within $f_{24\,\mu{\rm m}} \gtrsim 100\ \mu$Jy galaxies easily detectable by MIPS 24 μm. In this context our results imply that GRBs identified and localized with the current techniques cannot be used as unbiased probes of the global star formation in the early universe.

2. The detection of the GRB 970828 host by MIPS at 24 μm strongly supports the idea that some of the so-called dark bursts can be explained by the effect of dust extinction within their host galaxy. Even though the hosts of the two other dark GRBs in our sample (GRB 981226 and GRB 990506) were not detected, this could indicate that the currently GRB-selected sources are biased against dusty starbursts. In the near future the localization of GRB hosts using X-ray afterglows detected with the XRT instrument on board *Swift* will provide new insights on this potential bias.

3. The host of GRB 010222 that has been claimed to be associated with a SCUBA/MAMBO galaxy at $z = 1.48$ is detected with neither IRAC nor MIPS, thus bringing strong doubt on the identification of this host at long wavelengths. Similarly, our nondetection of the host of GRB 970508 at $z = 0.84$ rules out the proposed association of this object with an ultraluminous infrared galaxy seen at 90 μm with ISOPHOT, and the nondetection of the host of GRB 980703 at 24 μm suggests that the radio emission previously detected in this object does not originate from massive star formation.

4. The observations of the host galaxies of GRB 980425 and GRB 980613 reveal that these bursts did not occur in the regions harboring the most active star-forming activity within their hosts. This favors a picture in which the production of GRBs does not exactly scale with *star formation* but also depends on other parameters that remain to be explored (e.g., age and chemical enrichment of the parent progenitor populations, initial mass function, and fraction of binary systems).

We acknowledge funding from the IRS and MIPS projects, which are supported by NASA through the Jet Propulsion Laboratory (subcontracts 1257184 and 960785), as well as the Spitzer Science Center for efficient technical support. This work benefited from data obtained with the Multimission Archive at the Space Telescope Science Institute (MAST) and from publicly available software with material credited to STScI, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. We are also particularly grateful to the team led by Holland et al. (2000a) for publicly providing reduced *HST* data from their "Survey of the Host Galaxies of Gamma-Ray Bursts." We finally thank all our colleagues who shared with us stimulating discussions related to this work, as well as Ranga-Ram Chary and our anonymous referee for critical comments on the manuscript.

REFERENCES

Appleton, P. N., et al. 2004, ApJS, 154, 147
Armus, L., et al. 2004, ApJS, 154, 178
Barmby, P., et al. 2004, ApJS, 154, 97
Barnard, V. E., et al. 2003, MNRAS, 338, 1
Bell, E. F., McIntosh, D. H., Katz, N., & Weinberg, M. D. 2003, ApJS, 149, 289
Bell, E. F., et al. 2005, ApJ, 625, 23
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
———. 2005, ApJ, 634, 501
Blain, A. W., & Natarajan, P. 2000, MNRAS, 312, L35
Blain, A. W., Smail, I., Ivison, R. J., & Kneib, J.-P. 1999, MNRAS, 302, 632
Blain, A. W., Smail, I., Ivison, R. J., Kneib, J.-P., & Frayer, D. T. 2002, Phys. Rep., 369, 111
Bloom, J. S., Berger, E., Kulkarni, S. R., Djorgovski, S. G., & Frail, D. A. 2003, AJ, 125, 999
Bloom, J. S., Djorgovski, S. G., & Kulkarni, S. R. 2001a, ApJ, 554, 678
Bloom, J. S., Djorgovski, S. G., Kulkarni, S. R., & Frail, D. A. 1998, ApJ, 507, L25
Bloom, J. S., Kulkarni, S. R., & Djorgovski, S. G. 2002, AJ, 123, 1111
Bloom, J. S., Kulkarni, S. R., Galama, T. J., Frail, D. A., & Djorgovski, S. G. 2001b, GCN Circ. 1134, http://gcn.gsfc.nasa.gov/gcn/gcn3/1134.gcn3
Bloom, J. S., et al. 1999, ApJ, 518, L1
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Chapman, S. C., Blain, A. W., Ivison, R. J., & Smail, I. R. 2003, Nature, 422, 695
Charmandaris, V., et al. 2004, ApJS, 154, 142
Chary, R., Becklin, E. E., & Armus, L. 2002, ApJ, 566, 229
Chary, R., & Elbaz, D. 2001, ApJ, 556, 562
Chary, R., et al. 2004, ApJS, 154, 80
Christensen, L., Hjorth, J., & Gorosabel, J. 2004, A&A, 425, 913
Condon, J. J. 1992, ARA&A, 30, 575
Conselice, C. J., et al. 2005, ApJ, 633, 29
Courty, S., Björnsson, G., & Gudmundsson, E. H. 2004, MNRAS, 354, 581
Cowie, L. L., Barger, A. J., Fomalont, E. B., & Capak, P. 2004, ApJ, 603, L69
Cowie, L. L., Songaila, A., Hu, E. M., & Cohen, J. G. 1996, AJ, 112, 839
Dale, D. A., Helou, G., Contursi, A., Silbermann, N. A., & Kolhatkar, S. 2001, ApJ, 549, 215
Dale, D. A., et al. 2005, ApJ, 633, 857
Dickinson, M., Papovich, C., Ferguson, H. C., & Budavári, T. 2003, ApJ, 587, 25
Djorgovski, S. G., Bloom, J. S., & Kulkarni, S. R. 2003, ApJ, 591, L13
Djorgovski, S. G., Frail, D. A., Kulkarni, S. R., Bloom, J. S., Odewahn, S. C., & Diercks, A. 2001, ApJ, 562, 654
Djorgovski, S. G., Kulkarni, S. R., Bloom, J. S., Goodrich, R., Frail, D. A., Piro, L., & Palazzi, E. 1998, ApJ, 508, L17
Egami, E., et al. 2004, ApJS, 154, 130
Elbaz, D., Flores, H., Chanial, P., Mirabel, I. F., Sanders, D., Duc, P.-A., Cesarsky, C. J., & Aussel, H. 2002, A&A, 381, L1
Farrah, D., et al. 2003, MNRAS, 343, 585
Fazio, G. G., et al. 2004, ApJS, 154, 10
Flores, H., et al. 1999, A&A, 343, 389
Förster Schreiber, N. M., Sauvage, M., Charmandaris, V., Laurent, O., Gallais, P., Mirabel, I. F., & Vigroux, L. 2003, A&A, 399, 833
Fox, D. W., et al. 2003, ApJ, 586, L5

Frail, D. A., et al. 1999, ApJ, 525, L81
———. 2002, ApJ, 565, 829
Franceschini, A., Aussel, H., Cesarsky, C. J., Elbaz, D., & Fadda, D. 2001, A&A, 378, 1
Franceschini, A., et al. 2003, A&A, 403, 501
Frayer, D. T., et al. 2004, ApJS, 154, 137
Fruchter, A., Hook, R., & Pian, E. 2000a, GCN Circ. 757, http://gcn.gsfc.nasa.gov/gcn/gcn3/757.gcn3
Fruchter, A., Vreeswijk, P., & Nugent, P. 2001, GCN Circ. 1029, http://gcn.gsfc.nasa.gov/gcn/gcn3/1029.gcn3
Fruchter, A. S. 1999, ApJ, 512, L1
Fruchter, A. S., et al. 1999, ApJ, 519, L13
———. 2000b, ApJ, 545, 664
Fynbo, J. P. U., et al. 2003, A&A, 406, L63
Fynbo, J. U., et al. 2000, ApJ, 542, L89
———. 2001, A&A, 369, 373
Galama, T. J., et al. 1998, Nature, 395, 670
Gorosabel, J., et al. 2005, A&A, 444, 711
Gruppioni, C., Pozzi, F., Zamorani, G., Ciliegi, P., Lari, C., Calabrese, E., La Franca, F., & Matute, I. 2003, MNRAS, 341, L1
Hammer, F., Flores, H., Elbaz, D., Zheng, X. Z., Liang, Y. C., & Cesarsky, C. 2005, A&A, 430, 115
Hammer, F., Gruel, N., Thuan, T. X., Flores, H., & Infante, L. 2001, ApJ, 550, 570
Hanlon, L., et al. 2000, A&A, 359, 941
Harper, D. A., & Low, F. J. 1971, ApJ, 165, L9
Heger, A., Fryer, C. L., Woosley, S. E., Langer, N., & Hartmann, D. H. 2003, ApJ, 591, 288
Higdon, J. L., et al. 2005, ApJ, 626, 58
Hirschi, R., Meynet, G., & Maeder, A. 2005, A&A, 443, 581
Hjorth, J., et al. 2002, ApJ, 576, 113
———. 2003, Nature, 423, 847
Holland, S., & Hjorth, J. 1999, A&A, 344, L67
Holland, S., et al. 2000a, GCN Circ. 698, http://gcn.gsfc.nasa.gov/gcn/gcn3/698.gcn3
———. 2000b, GCN Circ. 731, http://gcn.gsfc.nasa.gov/gcn/gcn3/731.gcn3
———. 2000c, GCN Circ. 749, http://gcn.gsfc.nasa.gov/gcn/gcn3/749.gcn3
———. 2001, A&A, 371, 52
Houck, J. R., et al. 2004, ApJS, 154, 18
Huang, J.-S., et al. 2005, ApJ, 634, 137
Ivison, R. J., et al. 2004, ApJS, 154, 124
Izzard, R. G., Ramirez-Ruiz, E., & Tout, C. A. 2004, MNRAS, 348, 1215
Jaunsen, A. O., et al. 2003, A&A, 402, 125
Jha, S., et al. 2001, ApJ, 554, L155
Juneau, S., et al. 2005, ApJ, 619, L135
Kasliwal, M. M., Charmandaris, V., Weedman, D., Houck, J. R., Le Floc'h, E., Higdon, S. J. U., Armus, L., & Teplitz, H. I. 2005, ApJ, 634, L1
Kawai, N., Yamada, T., Kosugi, G., Hattori, T., & Aoki, K. 2005, GCN Circ. 3937, http://gcn.gsfc.nasa.gov/gcn/gcn3/3937.gcn3
Kennicutt, R. C., Jr. 1998, ARA&A, 36, 189
Kouveliotou, C., Meegan, C. A., Fishman, G. J., Bhat, N. P., Briggs, M. S., Koshut, T. M., Paciesas, W. S., & Pendleton, G. N. 1993, ApJ, 413, L101
Kulkarni, S. R., et al. 1998, Nature, 393, 35
———. 1999, Nature, 398, 389
Lagache, G., Dole, H., & Puget, J.-L. 2003, MNRAS, 338, 555
Lagache, G., et al. 2004, ApJS, 154, 112
Lamb, D. Q., & Reichart, D. E. 2000, ApJ, 536, 1
Le Floc'h, E., et al. 2002, ApJ, 581, L81
———. 2003, A&A, 400, 499
———. 2005, ApJ, 632, 169
MacFadyen, A. I., & Woosley, S. E. 1999, ApJ, 524, 262
Malesani, D., et al. 2004, ApJ, 609, L5
Melbourne, J., Koo, D. C., & Le Floc'h, E. 2005, ApJ, 632, L65
Meynet, G., & Maeder, A. 2005, A&A, 429, 581
Mirabel, I. F. 2004a, in 5th INTEGRAL Workshop on the INTEGRAL Universe, ed. V. Schönfelder, G. Lichti, & C. Winkler (ESA SP-552; Noordwijk: ESA), 175
———. 2004b, Rev. Mex. AA Conf. Ser., 20, 14
Mirabel, I. F., Sanders, D. B., & Le Floc'h, E. 2000, in ASP Conf. Ser. 215, Cosmic Evolution and Galaxy Formation, ed. J. Franco et al. (San Francisco: ASP), 192
Odewahn, S. C., et al. 1998, ApJ, 509, L5
Piro, L., et al. 2000, Science, 290, 955
Podsiadlowski, P., Mazzali, P. A., Nomoto, K., Lazzati, D., & Cappellaro, E. 2004, ApJ, 607, L17
Prochaska, J. X., et al. 2004, ApJ, 611, 200
Puget, J.-L., Abergel, A., Bernard, J.-P., Boulanger, F., Burton, W. B., Désert, F.-X., & Hartmann, D. 1996, A&A, 308, L5
Ramirez-Ruiz, E., Lazzati, D., & Blain, A. W. 2002, ApJ, 565, L9
Reeves, J. N., et al. 2002, Nature, 416, 512
Richards, E. A. 2000, ApJ, 533, 611
Rieke, G. H., et al. 2004, ApJS, 154, 25
Roussel, H., Sauvage, M., Vigroux, L., & Bosma, A. 2001, A&A, 372, 427
Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 749
Saracco, P., Chincarini, G., Covino, S., Ghisellini, G., Longhetti, M., Zerbi, F., Lazzati, D., & Severgnini, P. 2001, GCN Circ. 1032, http://gcn.gsfc.nasa.gov/gcn/gcn3/1032.gcn3
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Silva, L., Granato, G. L., Bressan, A., & Danese, L. 1998, ApJ, 509, 103
Smail, I., Chapman, S. C., Blain, A. W., & Ivison, R. J. 2004, ApJ, 616, 71
Soderberg, A. M., et al. 2004, ApJ, 606, 994
Sokolov, V. V., et al. 2001, A&A, 372, 438
Spergel, D. N., et al. 2003, ApJS, 148, 175
Spoon, H. W. W., et al. 2004, ApJS, 154, 184
Stanek, K. Z., et al. 2003, ApJ, 591, L17
Stetson, P. B. 1987, PASP, 99, 191
Tanvir, N. R., et al. 2004, MNRAS, 352, 1073
Taylor, G. B., Bloom, J. S., Frail, D. A., Kulkarni, S. R., Djorgovski, S. G., & Jacoby, B. A. 2000, ApJ, 537, L17
Tinney, C., et al. 1998, IAU Circ., 6896, 1
Venemans, B. P., & Blain, A. W. 2001, MNRAS, 325, 1477
Vreeswijk, P. M., et al. 1999, ApJ, 523, 171
———. 2001, ApJ, 546, 672
Weedman, D. W., et al. 2005, ApJ, 633, 706
Werner, M. W., et al. 2004, ApJS, 154, 1
Wijers, R. A. M. J., Bloom, J. S., Bagla, J. S., & Natarajan, P. 1998, MNRAS, 294, L13
Zheng, X. Z., Hammer, F., Flores, H., Assémat, F., & Pelat, D. 2004, A&A, 421, 847