THE NATURE OF GRB-SELECTED SUBMILLIMETER GALAXIES: HOT AND YOUNG

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ABSTRACT

We present detailed fits of the spectral energy distributions (SEDs) of four submillimeter galaxies selected by the presence of a gamma-ray burst (GRB) event (GRBs 980703, 000210, 000418, and 010222). These faint ~3 mJy submillimeter emitters at redshift $z \sim 1$ are characterized by an unusual combination of long- and short-wavelength properties, namely enhanced submillimeter and/or radio emission combined with optical faintness and blue colors. We exclude an active galactic nucleus as the source of long-wavelength emission. From the SED fits, we conclude that the four galaxies are young (ages <2 Gyr), highly star forming (star formation rates $\sim 150 \, M_\odot \, yr^{-1}$), low mass (stellar masses $\sim 10^{10} \, M_\odot$), and dusty (dust masses $\sim 3 \times 10^8 \, M_\odot$). Their high dust temperatures ($T_d > 45 \, K$) indicate that GRB host galaxies are hotter, younger, and less massive counterparts to the submillimeter-selected galaxies detected so far. Future facilities like Herschel, the James Clerk Maxwell Telescope SCUBA-2, and ALMA will test this hypothesis, enabling measurement of dust temperatures of fainter GRB-selected galaxies.

Subject headings: dust, extinction — galaxies: evolution — galaxies: high-redshift — galaxies: ISM — galaxies: starburst — gamma rays: bursts

Online material: color figures

1. INTRODUCTION

It has been claimed that submillimeter galaxies (SMGs; see Blain et al. 2002 for a review) are significant contributors to the star formation history of the universe at redshifts $z \sim 2$–3 (Chapman et al. 2005) and have built up a substantial fraction of the present-day stellar population (Lilly et al. 1999). SMGs are luminous (with infrared luminosities $L_{IR} \sim 10^{12}$–$10^{14} \, L_\odot$) and cold (with mean dust temperature $T_d = 36 \pm 7 \, K$; Chapman et al. 2005). Galaxies with similar luminosities but higher dust temperatures ($T_d > 45 \, K$) are difficult to detect in the submillimeter with current technology due to the fact that the peak of the infrared dust emission is shifted out of the sensitive 850 $\mu$m band toward shorter wavelengths (Blain et al. 2004; Chapman et al. 2004, 2005) in such galaxies.

At the other end of the galaxy luminosity function, the host galaxies of long-duration gamma-ray bursts (GRBs, which originate in the collapses of very massive stars at the end of their evolution; e.g., Stanek et al. 2003; Hjorth et al. 2003b) do not have much in common with SMGs, except for the fact that this type of galaxy is also thought to contribute significantly to, or at least trace, the global star formation (e.g., Jakobsson et al. 2005, 2006b). In contrast to SMGs, GRB hosts are found to be blue, subluminous in the optical (Le Floc’h et al. 2003; Fruchter et al. 2006), and metal-poor (Fynbo et al. 2003). The majority of them have not been detected at mid-infrared (MIR), submillimeter, or radio wavelengths (Hanlon et al. 2000; Le Floc’h et al. 2006; Tanvir et al. 2004; Berger et al. 2003; Priderley et al. 2006), indicating that, as a class, they are not heavily obscured or violently star-forming galaxies. A low internal dust content is consistent with the low extinction found in the analysis of afterglows (Stratta et al. 2004; Chen et al. 2006; Kann et al. 2006) and the optical spectral energy distributions (SEDs) of the host galaxies (Christensen et al. 2004). However, four GRB hosts (980703, 000210, 000418, and 010222) have been firmly detected in submillimeter and/or radio (Tanvir et al. 2004; Berger et al. 2001b, 2003), providing a somewhat complex picture: assuming that this emission is powered by starbursts, the derived star formation rates (SFRs) are on the order of a few hundred solar masses per year, and the amount of dust in these galaxies is significant. On the other hand, they exhibit blue colors, low extinction, and low extinction-corrected optical/UV SFRs (Djorgovski et al. 1998; Holland et al. 2001; Sokolov et al. 2001; Chary et al. 2002; Gorosabel et al. 2003a, 2003b; Galama et al. 2003; Berger et al. 2003; Savaglio et al. 2003; Christensen et al. 2004; Chen et al. 2006; Kann et al. 2006), like the majority of known GRB hosts. This puzzling situation was highlighted by Berger et al. (2003; see their Fig. 3); these GRB hosts are much fainter in the optical than the prototypical ultraluminous infrared galaxy (ULIRG) Arp 220, and have much bluer spectra, but are more luminous in submillimeter and radio. In fact, no template SED model (e.g., Silva et al. 1998; Dale et al. 2001; Dale & Helou 2002) could give consistency with the data (see also Michalowski & Hjorth 2007; Michalowski 2006). Moreover, none of these hosts have been detected at 24 $\mu$m (Le Floc’h et al. 2006; Castro Cerón et al. 2006; E. Le Floc’h 2007, private communication).

The location of the GRB events within their hosts adds further complexity to this picture. As found by Fruchter et al. (2006), GRBs trace the location of the brightest rest-UV parts of their hosts (see also Bloom et al. 2002). If the majority of the star formation in the hosts of GRBs 980703, 000210, 000418, and 010222 were hidden by dust, then they should preferentially be found in obscured (UV-dim) parts of their hosts (as long as GRBs trace star formation), which is contrary to observations.

In this paper, we investigate this seeming discrepancy between short- and long-wavelength data through stellar population model SED fitting. In particular, we discuss the possibility that these submillimeter-bright GRB hosts may represent the long-sought hotter (and less luminous) counterparts of SMGs. In § 2 we describe the model and the fitting procedure, in § 3 we show the results, we discuss their implication in § 4, and finally in § 5 we conclude this work. We use a cosmological model with $H_0 = 70 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$, $\Omega_\Lambda = 0.7$, and $\Omega_M = 0.3$. 

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2. GRASIL SED MODELING

In order to model the SEDs of GRB hosts, we used the GRASIL1 software developed by Silva et al. (1998). GRASIL is a numerical code that calculates the spectrum of a galaxy by means of a two-dimensional radiative transfer method, applied to photons produced by a stellar population, and reprocessed by dust. This model is self-consistent in that it fulfills the principle of energy conservation between the energy absorbed by dust in the UV/optical wavelengths and the energy re-emitted in the infrared. Two extinction media are implemented: dense star-forming molecular clouds (MCs, applied only to the youngest stellar population) and diffuse cirrus. The dust is composed of small grains (not in thermal equilibrium with radiation, and hence fluctuating in temperature), big grains (silicates and graphites), and polycyclic aromatic hydrocarbon (PAH) molecules. The emission of grains with a given size is assumed to be a graybody, so the composite spectrum is a sum of all graybodies with different temperatures. A galaxy is assumed to be an axially symmetric system. Different geometries of the stellar and diffuse dust distributions are allowed, but were not used here. The SRF is assumed to be proportional to the available gas content following the Schmidt law. On top of this smooth SFR history, a violent starburst epoch is added. Star formation is unevenly distributed throughout the galaxy in MCs. The SRF given as a GRASIL output is the sum of the SRFs of each MC.

We gathered photometric data from the literature at optical (Sokolov et al. 2001; Vreeswijk et al. 1999; Gorosabel et al. 2003a, 2003b; Galama et al. 2003), infrared (Castaño Cerón et al. 2006; Le Floc’h et al. 2006), submillimeter (Tanvir et al. 2004; Berger et al. 2003), and radio (Berger et al. 2001b, 2003; Frail et al. 2002; Sagar et al. 2001) wavelengths. For the host of GRB 000210, we performed the photometry on the archival Spitzer Space Telescope images (see Castro Cerón et al. 2006; J. M. Castro Cerón et al. 2007, in preparation, for a description of the procedure), and obtained the following fluxes: $3.3 \pm 2.1 \, \mu \text{Jy}$ at 4.5 $\mu$m, $15.0 \pm 5.1 \, \mu \text{Jy}$ at 8.0 $\mu$m, and $<31.5 \, \mu \text{Jy}$ at 24 $\mu$m ($3 \sigma$).

We performed SED modeling investigating a wide range of the following GRASIL parameters: the age of the galaxy (defined as the time since the beginning of its evolution, when the stellar population started to build up), the dust-to-gas ratio, and the mass of gas converted into stars during the current starburst episode (lasting 50 Myr). We used a clearing time for MCs, $t_{\text{clear}} = 50$ Myr (see Panuzzo et al. 2007 for discussion of this parameter).

3. RESULTS

The best fits2 are shown in Figure 1, and the results for each parameter are listed in Table 1, together with several properties of the galaxies derived from the SEDs. SFRs, stellar masses, dust masses, and extinction in the MCs are given as output from GRASIL. Infrared luminosities were obtained by integrating the SEDs over a range of 8–1000 $\mu$m. Dust temperatures were estimated by fitting a graybody curve to the part of the SEDs near the dust peak (~100 $\mu$m; e.g., Yun & Carilli 2002). Finally, the average extinction outside MCs was calculated as $A_V = 2.5 \log(V\text{-band starlight extinguished by MCs only})/V\text{-band starlight observed})$. We obtained much higher extinction for the host of GRB 000210 than Christensen et al. (2004), but our model predicts that the majority of the extinction in the V-band has a gray nature, which would be undetectable in any reddening measurements (we found $E(B-V) = 0.07$, which is consistent with their results if one assumes a Galactic extinction curve slope $R_V = 3.1$). Moreover, it is possible that a GRB event destroys the dust along the line of sight, so that study of an afterglow results in low dust content.

The determination of the infrared luminosity suffers from systematic uncertainties, depending on the choice of the SED template. Our approach of using all the optical, submillimeter, and radio data to constrain the shape of the SED results in a moderate systematic error in luminosity. Using the templates of Dale et al. (2001) and Dale & Helou (2002) fitted to long-wavelength data, we obtained values only 30% lower. Similar analysis on a bigger sample of galaxies led Bell et al. (2007) to the conclusion that the systematic uncertainty of infrared luminosity is usually less than a factor of ~2. The arbitrary choice of the Salpeter (1955) initial mass function, with cutoffs of 0.15 and 120 $M_{\odot}$, introduces a systematic error of a factor of ~2 in the determination of the stellar masses and SFRs (Erb et al. 2006). Bell et al. (2007) have also found that random errors in stellar mass are less than a factor of ~2. Dust mass estimates are uncertain up to a factor of a few (Silva et al. 1998). Estimates of dust temperatures based on submillimeter and radio alone have uncertainties of ~10 K (Chapman et al. 2003).

4. DISCUSSION

4.1. Solving the Puzzle

The key property of GRB hosts that explains their blue colors and enhanced submillimeter/radio emission is their young ages (Table 1). On the one hand, the majority of the stars still reside in dense MCs, so a significant part of the energy is absorbed and
re-emitted. This increases the dust emission. On the other hand, there are lots of young, hot, blue stars in such a galaxy, because they have not finished their lives yet. Hence, the total optical spectrum of the galaxy is blue. GRBs may indeed reside in or close to MCs (possibly causing hydrogen ionization and dust sublimation along the line of sight; Watson et al. 2007), and it was found that gas column densities derived from X-ray afterglows in a sample of eight GRBs (including GRB 980703, discussed here) were in the range corresponding to the column densities of giant MCs in the Milky Way (Galama & Wijers 2001). A similar conclusion for high-redshift GRBs was recently drawn by Jakobsson et al. (2006a) by means of modeling Lyα absorption features (see also Castro-Tirado et al. 1999; Hjorth et al. 2003a; Savaglio et al. 2003; Stratta et al. 2004; Vreeswijk et al. 2004; Chen et al. 2005, 2006; Watson et al. 2006; Campana et al. 2007; Prochaska et al. 2007b, 2007a; Ruiz-Velasco et al. 2007 for a discussion of similar results).

Since the stars formed during the starburst do not dominate the stellar mass of the GRB hosts discussed here (only from 10% to 40% of these masses have been formed during the ongoing starburst epoch; compare cols. [5] and [8] of Table 1) and are still embedded in MCs providing strong extinction (so-called age-dependent extinction; see Panuzzo et al. 2007), it is apparent that the optical/UV light is dominated by somewhat older stars, which are already outside MCs, and suffer only moderate extinction (col. [12] in Table 1; see Plante & Sauvage 2002 for an example of a totally obscured, metal-poor star-forming region). This is why optical measurements of extinction have resulted in low values, suggesting low dust content, whereas enhanced submillimeter emission is consistent with being emitted by dusty galaxies. In light of this, we provide support for the hypothesis of Gorosabel et al. (2003a), claiming that the optical and submillimeter emission of the host of GRB 000210 are dominated by different populations of stars (the same explanation was proposed by Goldader et al. 2002 for a sample of dusty ULIRGs, with UV colors that were bluer than expected for starburst galaxies).

The location of GRBs in the brightest UV parts of the galaxy (Fruchter et al. 2006) is also consistent with our model. Although the GRBs discussed here trace regions of obscured rather than non-obscured star formation (because the majority of star formation

![Graph](image-url)
is obscured and under the assumption that GRBs trace star formation, these regions are not spatially distinct in the galaxy. Regions of obscured star formation evolve into nonobscured regions by destroying the MCs without changing their location. Unless individual MCs can be resolved, obscured star formation within them and less obscured star formation on their outskirts cannot be spatially separated.

Our results are based on the assumption that the detected submillimeter/radio sources are indeed related to GRB hosts. It is, however, possible that the emission comes from unrelated sources falling into the coarse beam of SCUBA (15'), as noted by Smith et al. (2001, 2005), Gorosabel et al. (2003a), and Le Floc'h et al. (2006). The most suspicious case is the host of GRB 010222, which is undetected at 24 μm, but accompanied by several spatially close MIR-bright galaxies that could dominate the submillimeter emission (Le Floc'h et al. 2006). On the other hand, the non-detections of GRB hosts in the MIR are easily explained by silicate absorption features and the steep infrared spectrum of the galaxies (see Fig. 1). The situation is less severe for GRB 980703 and GRB 000418, both detected by VLA in the radio, for which accurate astrometry decreases the chance of confusion.

4.2. The Nature of the GRB Hosts

From the results presented in Table 1, a common characteristic of submillimeter/radio sources detected in our sample of GRB hosts is the absence of a nearby bright AGN. Surveys with HST and Spitzer have found no AGN in the fields of any of these four galaxies. All four galaxies are relatively small, with a diameter of 20 kpc. They also have low stellar masses (≤10^{10} M_☉). These properties are consistent with the general characteristics of GRB hosts. Moreover, the luminosity of the host galaxy is usually low, with a luminosity of only 10^{4} L_☉. The X-ray luminosity is high enough to place it at the borderline of the category of dark GRBs; Jakobsson et al. 2004; Rol et al. 2005; both of these facts hint at significant obscuration in the hosts. However, the “darkness” of GRBs cannot easily be linked with obscuration in the hosts, because the remaining three members of our submillimeter/radio sample were discovered with bright optical afterglows (Berger et al. 2001a; Bloom et al. 1998; Björnsson et al. 2002; Castro-Tirado et al. 1999; Galama et al. 2003; Holland et al. 2001; Klose et al. 2000; Vreeswijk et al. 1999). Moreover, Barnard et al. (2003) did not detect submillimeter emission from the hosts of three GRBs classified as dark. This issue should be addressed by targeting a more significant sample of dark GRBs in the submillimeter and radio.

4.3. Rejection of an AGN Contribution

In general, GRB hosts are typically starburst galaxies, and this selection makes the presence of an AGN component quite unlikely. Here we present additional indications that the long-wavelength emission from GRB hosts discussed here is not dominated by AGNs.

In order to assess the probability that there is an AGN component in our sample of GRB hosts, we compared their FIR and radio luminosities using the q coefficient of Helou et al. (1985):

\[ q = \log \frac{\text{FIR}}{\text{M}_\text{d}} \times 10^{27} \times 10^{3.75} \times \left( \frac{10^{12}}{M_\text{d}} \right) \]

The FIR luminosity was integrated in the range 42.5–122.5 μm. The rest 1.4 GHz luminosity (S_{\text{1.4 GHz}}) was calculated from the observed 1.4 GHz (or 4.86 GHz for GRB 010222) flux, assuming a steep radio slope α = −0.75 to obtain a robust lower limit on q. (Assuming a shallower slope, the expected rest 1.4 GHz radio luminosity would be even lower.)

The resulting q values are 2.28, 1.93, 2.41, and >2.06 for GRBs 980703, 000210, 000418, and 010222, respectively. It is known that starburst galaxies follow the so-called FIR-radio correlation with a slope of q = 2.12 ± 0.14 (Helou et al. 1985) or 2.3 ± 0.2 (Condon 1992). Hence the GRB hosts are consistent with being starburst-dominated galaxies. Emission dominated by radio-loud AGNs would show q < 2 (Yun et al. 2001; Chiang et al. 2007; Yang et al. 2007), which would only be the case for GRB 000210 if the actual radio flux were just below the 3 σ upper limit. We therefore conclude that the FIR-radio correlation shows that the emission from GRB hosts is probably not dominated by radio-loud AGNs. Even if a nondominating AGN is present, its contribution to the radio and submillimeter emission is insignificant, since the hosts fulfill the FIR-radio correlation. It would be rather unlikely that AGN-dominated emission is coincidentally consistent with tight FIR-radio correlation.

This is supported by several other diagnostics. Berger et al. (2001b) detected no variability in the radio flux of the host of GRB 980703 over 650 days, which is contrary to what would be...
expected if an AGN were to dominate its radio emission. Moreover, GRB hosts have optical spectra typical for starbursts, not AGNs (i.e., no high-ionization AGN lines have been found; Djorgovski et al. 1998; Berger et al. 2001b; Bloom et al. 2003; Prochaska et al. 2004). This excludes nonobscured AGNs in our sample. Moreover, GRB hosts are dwarf galaxies, and the fraction of AGNs (without optical high-ionization lines) in a galaxy sample with a stellar mass of $M_* \sim 10^{10} M_\odot$ is negligible (<0.1% from Fig. 2 of Best et al. 2005; see also Woo et al. 2005). AGNs are also more luminous than GRB hosts, as is shown in Figure 2. In summary, AGNs cannot dominate the emission of the GRB hosts discussed here unless they are atypically small, obscured, and radio-quiet. Since submillimeter- and radio-faint hosts are even less probably connected with AGN activity (because it would require even smaller AGNs), we conclude that it is unlikely that GRB hosts in general are powered by AGNs.

4.4. The General Picture of Dust Properties

In Figure 2, we compare the total infrared luminosities and dust temperatures of GRB hosts with well-studied galaxies, both local and at high $z$. We included the four hosts studied here, as well as the host of GRB 030115, which has an upper limit to the temperature of 50 K. This limit was derived by Priddey et al. (2006) using SED modeling of optical and near-infrared data, which led to the estimation of the infrared luminosity via the UV-slope method. This, in turn, allowed them to exclude a low dust temperature, because cold dust would be inconsistent with the nondetection of the host in the submillimeter. GRB hosts seem to overlap with intermediate-$z$ ULIRGs from Yang et al. (2007). This is not very surprising, since both galaxy classes have ULIRG characteristics. GRB hosts, however, are much more distant. As opposed to a mean redshift of 0.37 for intermediate-$z$ ULIRGs, our sample has a mean redshift of 1.1, compared to 2.8 for GRBs in general (Jakobsson et al. 2006b), 2.2 for SMGs (Chapman et al. 2005), and 2.1 for optically faint radio galaxies (OFRGs, Chapman et al. 2004).

The GRB hosts discussed here occupy the same region of Figure 2 as the brightest starbursts from Taylor et al. (2005). Moreover, dust masses of GRB hosts (Table 1) are close to the upper boundary for starburst galaxies derived by these authors.

![Figure 2](https://example.com/figure2.png)

**Fig. 2.— Dust temperature as a function of infrared (8–1000 $\mu$m) luminosity. GRB hosts discussed here (filled squares) and GRB 030115 (arrow, indicating lower limit on temperature; Priddey et al. 2006) are compared with submillimeter galaxies (plus signs; Chapman et al. 2005; Kneib et al. 2005; the large plus denotes a hot lensed galaxy found behind a cluster), optically faint radio galaxies (triangles; note that symbols indicate lower limits on temperature; Chapman et al. 2004), intermediate-$z$ ULIRGs (crosses; Yang et al. 2007), local ULIRGs (asterisks; Solomon et al. 1997), local LIRGs (dots; Dunne et al. 2000), low-$z$ starburst galaxies (diamonds; Taylor et al. 2005), low-$z$ spirals and cirrus galaxies (stars; Stevens et al. 2005; Taylor et al. 2005), and millimeter-selected radio-quiet AGNs (circles; Benford et al. 1999; Beelen et al. 2006). GRB hosts seem to reflect the properties of intermediate-$z$ ULIRGs, the bright end of starburst galaxies, and optically faint radio galaxies, i.e., the candidates for hotter counterparts of SMGs. Moreover, the hot, faint SMG found behind the cluster (large plus) falls in the same region as GRB hosts. [See the electronic edition of the Journal for a color version of this figure.]**
As noted above, the GRB hosts discussed here must form the bright end of the infrared luminosity function of GRB hosts. The remaining members of the sample are still undetected at long wavelengths, making it impossible to measure luminosities and dust temperatures. One can speculate from Figure 2 that they may follow the “starburst” sequence, i.e., may have temperatures of 40–50 K and infrared luminosities in the range $10^9–10^{12} L_\odot$. Hörschel should be able to detect these sources in the FIR. There is also the possibility that we can detect even brighter (but rare) GRB hosts, the counterparts of the brightest ULIRGs of Yang et al. (2007), with luminosities $\sim 10^{13} L_\odot$ and temperatures $\sim 60$ K. These should be bright enough to be detectable by sensitive submillimeter instruments (JCMT SCUBA-2, ALMA).

It is known that GRB hosts are much bluer than massive, star-forming SMGs (cf. Christensen et al. 2004; Le Floc’h et al. 2003; Berger et al. 2003; Smail et al. 2004). From Figure 2, it seems that they are also hotter than SMGs that have the same luminosity (or dimmer than SMGs that have the same temperature). This gives a hint that GRB events may pinpoint a population of ULIRGs at high redshifts with dust that is hotter than in typical SMGs. The search for such galaxies is important, because they likely contribute to the star formation history at the same level as SMGs. High dust temperatures of GRB hosts were hypothesized by Barnard et al. (2003) and Tanvir et al. (2004) as a possible way to explain the faintness in the submillimeter. Here we provide evidence that this is the case. Moreover, Trentham et al. (2002) suggested that GRB hosts may be low-luminosity SMGs. Indeed, very faint sub-mJy SMGs magnified by clusters of galaxies are found to be hotter than those found in blind surveys (limited by confusion to $\sim 2$ mJy): the $T_d$ $\sim 2.5$ SMG behind the cluster A 2218 found by Kneib et al. (2005) has very similar dust properties to the GRB hosts discussed here ($T_d \sim 50$, $L_{IR} \sim 10^{12} L_\odot$).

Hotter dust temperatures indicate that the star formation sites in GRB hosts are more compact than those in SMGs (Chanial et al. 2007; Yang et al. 2007). This is consistent with the fact that GRB hosts have higher specific SFRs (per unit mass) than SMGs (Castro Cerón et al. 2006). The blue optical colors of GRB hosts compared to SMGs can also be explained by the compactness of the former galaxies. If they are compact, then the stellar population suffers strong extinction. This would lead to redder colors, but it is likely (see § 4.1) that this extinction is so strong that very young stars are totally obscured, so optical light is dominated by relatively less obscured stars outside star-forming regions, leading to blue colors.

We note that the majority of the galaxies shown in Figure 2 also have higher dust temperatures than SMGs. However, all of them are local galaxies, and so cannot be considered as counterparts of high-redshift SMGs; their submillimeter emission has been detected only because of their proximity.

GRB hosts may be consistent with a population of OFRGs that have similar infrared luminosities and (likely) similar temperatures. Although the majority of OFRGs lie at $z \sim 2$ (Chapman et al. 2004), some of them are within the redshift range of the GRB hosts discussed here. It has been suggested that OFRGs are hotter counterparts of SMGs (Chapman et al. 2004), so the same may be true for GRB hosts.

Indeed SMG samples are clearly biased against the high-$T_d$–low-$L$ galaxies (upper left part of Fig. 2; see Chapman et al. 2005). The lack of SMGs in low-$T_d$–high-$L$ (lower right corner) is probably real, because such sources would be detected if they were present (see Fig. 2 of Blain et al. 2004 for a discussion of selection effects). Similarly, the lack of very luminous sources with $L > 10^{14} L_\odot$ is probably real. If such powerful sources exist, they are very rare, and do not contribute to the presented sample. Taking into account all the galaxies shown in Figure 2, the lack of high-$T_d$–low-$L$ galaxies is probably not a selection effect (at low redshift), because the hotter counterparts of $10^{10} L_\odot$ galaxies should be easily detected in MIR and FIR.

Therefore the apparent trend (also seen in our GRB host sample) that more luminous galaxies have higher dust temperatures is a real effect called the luminosity-temperature relation (Soifer et al. 1987; Chariel et al. 2007; Yang et al. 2007). The spread has been interpreted as variation in the size of a star-forming region (Chariel et al. 2007) or in the dust emissivity index and amount of dust in each galaxy (Yang et al. 2007). Galaxies with high dust content tend to occupy the lower right corner of Figure 2, whereas those with low dust content occupy the upper left corner. The GRB hosts discussed here with $M_L \sim 10^{8} M_\odot$ are placed near the average of all the galaxies shown in Figure 2. The rest of the population is probably aligned along the diagonal of Figure 2, fulfilling the luminosity-temperature relation. It is expected that some of the IR-faint GRB hosts have much lower dust content, and so are possibly located in the lower $L$ to higher $T_d$ regime.

5. CONCLUSIONS

The short- and long-wavelength properties of the host galaxies of GRBs 980703, 000210, 000418, and 010222 can be linked, assuming that they are very young and powerful starbursts. We conclude that they are galaxies with the highest star formation rates among known GRB hosts, but that their optical properties, starburst nature, stellar masses, and ages are not distinctive. We also find that AGNs are probably not responsible for boosting their long-wavelength emission.

We have shown that GRB host galaxies at cosmological redshifts may constitute a population of hot submillimeter galaxies. This hypothesis makes GRB hosts of special interest, placing them in the same category as optically faint radio galaxies, and should be confirmed by future sensitive long-wavelength observations. Future instruments (Herschel, JCMT SCUBA-2, and ALMA) will be able to build up a statistically significant sample of GRB hosts with accurately measured infrared luminosities and temperatures.

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APPENDIX

COMPARISON OF OUR RESULTS WITH THE LITERATURE

In the following appendix, we compare our results with those found by other authors applying different methods, to show that our modeling in most cases gives consistent values, but also provides additional galaxy properties that cannot be inferred from previous
approaches. We stress that some inconsistency with methods based on optical/UV is expected, because optical/UV light traces only a minor (i.e., unobscured) portion of the bolometric luminosity of the galaxies. Some authors used different IMFs, but the necessary correction to total SFRs and stellar masses is not larger than 15%, and does not affect the conclusions of the comparison.

A1. AGES

Based on galaxy SEDs fitted to the optical data only, Gorosabel et al. (2003a, 2003b) and Christensen et al. (2004) derived the ages of the starbursts in the hosts of GRBs 980703, 000210, and 000418. Our estimates are considerably larger only for GRB 980703. This discrepancy results because we calculated the time from the beginning of the galaxy evolution, not the beginning of the starburst. Sokolov et al. (2001) derived ages of both old stellar populations and starbursts. Our estimation for GRB 980703 agrees with the age of the old component, which is conceptually closer to our definition of the galaxy age. Ages derived by Takagi et al. (2004) for GRBs 000210, 000418, and 010222 agree with our results within a factor of a few.

A2. STAR FORMATION RATES

See Michalowski & Hjorth (2007) for details of the comparison between SFR estimates. Since the starburst is still hidden in MCs and its optical light is extinguished, SFRs derived from optical indicators (Christensen et al. 2004; Gorosabel et al. 2003a, 2003b; Berger et al. 2003) are 2 orders of magnitude lower than our estimates. Our results are consistent with radio-derived SFRs (Berger et al. 2003). This is because the calibration of SFR to radio flux requires the prior assumption of only two parameters (a normalization factor and a spectral index; see Yun & Carilli 2002), which are relatively well constrained. Our values also agree with the upper limits derived by Castro Ceron et al. (2006) using the template of Arp 220. Finally, Berger et al. (2003) obtained systematically higher SFRs by a factor of 2–5 based on submillimeter alone. We have checked that the SFRs derived from our SED models using the total infrared emission (Kennicutt 1998) are consistent with our values derived here (see Michalowski & Hjorth 2007).

A3. STELLAR MASSES

Our results for the host of GRB 980703 agree with the stellar mass derived by Castro Ceron et al. (2006) and with both stellar and burst masses derived by Sokolov et al. (2001). The stellar mass derived by J. M. Castro Ceron et al. (2007, in preparation) for GRB 000210 is also in agreement with our value.

A4. DUST PROPERTIES

Our value of the dust mass for the host of GRB 980703 agrees within a factor of 1.5 with the one derived by Castro Ceron et al. (2006). Dust masses derived by Takagi et al. (2004) for GRBs 000210, 000418, and 010222 agree with our results to within a factor of a few. We have checked that for these three hosts, values of dust masses computed directly from submillimeter fluxes (using Hildebrand 1983 and Taylor et al. 2005) agree with those reported here (see Michalowski 2006).

The near-infrared extinction derived for MCs (col. [11] in Table 1) is within the typical values found in observations of compact star-forming regions (e.g., Scoville et al. 1998; Plante & Sauvage 2002; Hunt et al. 2005) and numerical simulations (e.g., Indebetouw et al. 2006; Goicoechea & Le Bourlot 2007; Panuzzo et al. 2007). Our values of average extinction outside MCs (AF; col. [12] in Table 1) are consistent with those derived from optical host SED modeling by Sokolov et al. (2001) for 980703 and Christensen et al. (2004) for 980703, 000210, and 000418. They are also consistent with the values derived from optical afterglow modeling by Berger et al. (2001a) for 000418, Björnsson et al. (2002) for 010222, Stratta et al. (2004) for 980703 and 010222, and Chen et al. (2006) for 980703, although they are not consistent with values derived for the host of GRB 000210, for which we predict higher extinction, but which has a gray nature undetectable in any reddening measurements. To the best of our knowledge, we present the first determination from the host galaxy SED fitting for GRB 010222.

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