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The submillimetre properties of gamma-ray burst host galaxies

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ABSTRACT

Long-duration gamma-ray bursts (GRBs) accompany the deaths of some massive stars and hence, because massive stars are short-lived, are a tracer of star formation activity. Given that GRBs are bright enough to be seen to very high redshifts and detected even in dusty environments, they should therefore provide a powerful probe of the global star formation history of the Universe. The potential of this approach can be investigated via submillimetre (submm) photometry of GRB host galaxies. Submm luminosity also correlates with star formation rate, so the distribution of host-galaxy submm fluxes should allow us to test the two methods for consistency. Here, we report new JCMT/SCUBA 850-μm measurements for 15 GRB hosts. Combining these data with results from previous studies, we construct a sample of 21 hosts with <1.4 mJy errors. We show that the distribution of apparent 850-μm flux densities of this sample is reasonably consistent with model predictions, but there is tentative evidence of a dearth of submm-bright (>4 mJy) galaxies. Furthermore, the optical/infrared properties of the submm-brightest GRB hosts are not typical of the galaxy population selected in submm surveys, although the sample size is still small. Possible selection effects and physical mechanisms which may explain these discrepancies are discussed.

Key words: stars: evolution – dust, extinction – galaxies: evolution – cosmology: observations – gamma-rays: bursts – infrared: galaxies.

1 INTRODUCTION

1.1 Gamma-ray bursts and star formation

The spectroscopic detection of an energetic supernova (SN2003dh) concurrent with GRB 030329 (Hjorth et al. 2003a; Stanek et al. 2003) has firmly established that long-duration (>2 s; Kouveliotou et al. 1993) gamma-ray bursts (GRBs) accompany the core-collapse of some class of massive stars.

Since massive stars are short-lived, this also confirms that GRBs are closely associated with star formation activity, a possibility already discussed by a number of authors (e.g. Wijers et al. 1998; Totani 1999; Blain & Natarajan 2000). The extreme luminosity of the prompt gamma-ray emission means that GRBs can be detected, if they exist, to very high redshifts, with minimal extinction by intervening gas or dust. This makes them potentially very powerful indicators of star formation to early times.

To date, spectroscopically confirmed redshifts have only been published for about three dozen bursts, although various schemes have been suggested to derive redshifts empirically from gamma-ray properties, such as the lag–luminosity (Norris, Marani & Bonnell 2000) and variability–luminosity relations (Reichart et al. 2001). These studies suggest that the redshift distribution of GRBs is broadly consistent with the emerging picture of the comoving star

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formation rate in the Universe having peaked sometime around redshifts 1–4, although uncertainties ramp up at higher redshifts (e.g. Lloyd-Ronning, Fryer & Ramirez-Ruiz 2002; Ramirez-Ruiz, Trentham & Blain 2002).

These results are interesting, but premature to the extent that we have limited knowledge of these luminosity correlations, and only rudimentary understanding of the relationship between the GRB rate and star formation rate (e.g. Krumholz, Thorsett & Harrison 1998). For instance, there is the possibility that the GRB rate and/or brightness depends also on other factors, such as metallicity, galactic environment, and certainly on any variations in the stellar initial mass function (IMF). These are difficult factors to disentangle, but important insights can be gained by comparing GRB rate with the star formation rate estimated by other means. Our programme is aimed at providing a more quantitative comparison of the star formation rate deduced by GRBs and that obtained from submillimetre (submm) luminosity, through direct study of the host galaxies of GRBs.

Existing methods of mapping the star formation history of the Universe rely on estimating the star formation rates of individual galaxies, and summing these up in redshift bins with some estimated correction for galaxies below the detection threshold (e.g. Adelberger & Steidel 2000), or by modelling the redshift distribution so as to fit integrated backgrounds (e.g. Blain et al. 1999a).

If GRBs reliably trace star formation, and we can quantify the relationship, then ultimately detection of their host galaxies will not be required for the purposes of mapping global star formation history. None the less, GRB hosts also uniquely allow us to study the star-forming galaxy luminosity function right to the faint end. An upshot may be a means to estimate the proportion of the total star formation which is going on in infrared (IR)-bright, dusty galaxies, optically bright galaxies and in fainter populations which are not selected in other surveys (e.g. Trentham, Ramirez-Ruiz & Blain 2002). To date, the best example of the power of GRB selection to probe the faintest end of the galaxy luminosity function is GRB 020124, whose host galaxy is undetected by the *Hubble Space Telescope* (*HST*) to $R = 29.5$ (Berger et al. 2002). This galaxy would not have been found in any direct imaging survey to date and yet observations of the afterglow show that the host has a high H I column density (making it a damped Lyα absorber) and a redshift of $z = 3.20$ (Hjorth et al. 2003b).

1.2 Mapping star formation in the submm

The power of submm studies for mapping the star formation history of the Universe is discussed in detail by Blain et al. (2002) and Smail et al. (2002). Briefly, in dusty systems ultraviolet (UV) radiation, predominantly from massive stars, is reprocessed by the dust and emitted in the far IR. This emission, which itself is unaffected by dust extinction, is thus proportional to the obscured star formation rate. At higher redshifts the peak of emission moves increasingly into the submm, with the beneficial consequence that at 850 μm the apparent luminosity of a galaxy of given intrinsic bolometric luminosity changes little from redshift $z \approx 0.5$ out to $z \approx 10$.

Submm surveys, combined with constraints from the intensity and spectrum of IR backgrounds, show that compared to the local Universe, the majority of high-redshift star formation appears to be taking place in dusty systems (Blain et al. 1999a), and much (although not the dominant part) of this in so-called ultraluminous infrared galaxies (ULIRGs: with IR luminosities $\gtrsim 10^{12}$ $L_{\odot}$). Low-redshift ULIRGs exist, but have around 1000 times lower comoving space density (Smail et al. 2002).

Potential drawbacks with submm surveys are: (a) At the 2 mJy confusion limit of SCUBA only about 30 per cent of the total submm background emission from *COBE*-FIRAS observations is resolved out. (b) Any individual galaxy may suffer some contamination of its 850-μm luminosity through heating from an obscured active galactic nucleus (AGN). Only about 10 per cent of submm galaxies with deep X-ray data appear to show evidence for a hard X-ray AGN (Almaini et al. 2003), but larger samples and deeper observations will be necessary to confirm this fraction. (c) It is necessary to assume or constrain the shape of the far-IR spectral energy distribution (SED) at wavelengths shorter than 850 μm in order to translate the measured submm flux density into an accurate luminosity and star formation rate. The luminosity inferred from a galaxy with a certain SED depends only weakly on redshift; however, without direct knowledge of the details of the SED this luminosity is uncertain, leading to ambiguity in the results. A certain fractional change in the dust temperature leads to a fractional uncertainty in the inferred luminosity that is greater by several times (Blain et al. 2002; Blain, Barnard & Chapman 2003). While results are so far generally consistent with dust temperatures of order 35 K (Chapman et al. 2003a), the extent of the distribution of values is not yet known.

Redshifts for large samples of submm galaxies were for a long time hard to obtain, because of the lack of both bright optical counterparts (frequently $I > 26$), and the poor 15-arcsec spatial resolution of SCUBA at 850 μm. However, Chapman et al. (2003b, see also Ivison et al. 2002) have demonstrated that about 65 per cent of submm galaxies brighter than 5 mJy are detected in very deep Very Large Array (VLA) radio maps, providing accurate subarcsec positions. Redshifts for around 40–50 per cent of these radio-detected submm galaxies can be obtained using Keck LRIS spectra (Chapman et al. 2003a). Based on these results they find a range of redshifts from 0.8 to 2.8 with a median of 2.4, and conclude it is likely that most submm galaxies lie at redshifts between 2 and 3. The radio selection could be biased to lower redshifts, and to sources containing AGN; however, the reasonable $\simeq$40 per cent completeness of the redshift determinations of Chapman et al. suggests that these effects are not too significant.

On the other hand, in a recent study of the evolution of the global stellar mass density $0 < z < 3$ based on an infrared-selected sample of galaxies from the Hubble Deep Field North, Dickinson et al. (2003) report that while the star formation rate essentially tracks that determined in other wavebands at low redshifts, the rate at $z > 2$ is significantly different. These observations appear to be inconsistent with scenarios in which the bulk of stars in present-day galactic spheroids formed at $z \gg 2$, since most of the stars (50–75 per cent) of the present-day stellar mass density formed by $z \sim 1$ and in fact by $z = 2.7$ only 3–14 per cent of today's stars were present. The issue is clearly not settled.

Current sensitivities and confusion limits imply that substantially fainter submm samples will not be studied in detail until the ALMA interferometer is commissioned in 2012. Hence, an alternative method to probe the star formation in obscured galaxies is definitely required, and GRB source counts and host galaxy studies may ultimately be able to tell us both when and where this star formation occurred.

1.3 Pros and cons of GRBs as star formation indicators

Several characteristics of GRBs lend them to probing high-redshift star formation. (a) They are bright enough to be seen to $z \sim 20$ (e.g. Lamb & Reichart 2000). (b) They can be detected in gamma-rays through large columns of dust and gas. (c) They can be detected independently of whether a host galaxy can be found. Furthermore, much information relating to the host, such as redshift, metallicity, gas column density and extinction can all be obtained indirectly, from afterglow observations – either optically or X-ray. (d) The spectral slopes of both prompt and afterglow emission compensate to some extent for redshift dimming, and time dilation means that observations can be made earlier in the rest-frame time than would be the case for lower redshifts (e) being produced by individual massive stars, they are obviously unaffected by AGN contamination.

On the downside, GRBs are rare, their progenitors are still not fully understood and they are not very useful for telling us about the star formation rate in individual galaxies. In terms of the current observational state-of-play, samples of GRBs, particularly those with firm redshifts, are very inhomogeneous – the result of a wide variety of triggers and followup campaigns. One consequence is that, of the roughly 200 entries to-date in Jochen Greiner's web table[1] of 'well-localized' bursts, fewer than 25 per cent have optical afterglows identified. However, only a minority of those 200 were reported within 24 h, and had error circles <10 arcmin in diameter. Also, many were not well placed for optical observation, have only shallow limits, or in some cases no reported optical followup at all. Thus, the superficially high rate of 'dark' GRBs is misleading. The proportion of genuinely dark GRBs (a reasonable working definition would be $R > 23.5$ at 24 h post-burst; see also Section 2) amongst the *HETE* and *BeppoSAX* triggers is probably only 10–30 per cent.

The wide variation in GRB followup campaigns makes it hard to quantify selection effects, but selection effects may well be important for our study. To be found optically, an afterglow should not be in too dusty an environment. A low-redshift illustration of this issue is provided by Mannucci et al. (2003), who find an enhanced core-collapse supernova rate in *K*-band monitoring of nearby star-forming galaxies, but still conclude that the large majority of supernovae remain undetected due to very high extinction. In fact, for GRBs this conclusion is not as inevitable as it sounds because the initial flux of high-energy photons from GRBs is expected to destroy dust possibly up to $\sim$100 pc (e.g. Fruchter, Krolik & Rhoads 2001c; Galama & Wijers 2001). In some cases this will be enough to create a window through otherwise obscuring dust clouds. Of course, if most star formation in the Universe is occurring in the 'obscured mode', then dust destruction may actually be a *requirement* to explain the large number of afterglows detected optically. Even when optical afterglows are not found to faint limits, as we shall argue below, it is not necessarily the case that they are heavily enshrouded in dust. None the less, it would be surprising if some fraction of GRB afterglows were not missed because they were highly extinguished.

Detected afterglows are unlikely to be found in very low-density environments, even if GRBs occur there, since the brightness of the spectral peak reduces with the density of the ambient medium (Sari, Piran & Narayan 1998). The high H I column densities seen towards many bursts (e.g. Galama & Wijers 2001; Hjorth et al. 2003b) are consistent with this expectation, although Reichart & Price (2002) suggest that for the limited sample of dark bursts available, the column densities are not consistent with them being in the nuclear regions of ULIRGs either.

Observational limitations are also likely to introduce a bias against finding high-redshift GRBs. Although the spectral slope and cosmological time-dilation work so as to reduce the effect of redshift on the magnitude of an afterglow at a given observer time after the burst (another kind of negative *k*-correction), GRBs of comparable intrinsic luminosity will still appear fainter at higher redshift, making them and their afterglows harder to discover. For example, Hogg & Fruchter (1999) adopted a $(1+z)^{-1}$ dependence for the probability that a burst at a given redshift is detected and an optical afterglow found. Of course, $z \gtrsim 7$ objects will be essentially invisible in the optical due to the Lyα break.

Our initial goal is to compare the submm properties of GRB hosts with model predictions and hence provide a consistency check on both techniques for tracing star formation. Ultimately we would like to understand the quantitative relation between GRB rate and star formation rate, so that larger samples of GRBs may be used to give a good description of the global star formation history of the Universe.

2 PREVIOUS SUBMILLIMETRE STUDIES OF GRB HOSTS

The first submm limits and detections of GRB host galaxies came from observations aimed at detecting GRB afterglows. Only in a couple of cases were such fading afterglows detected, but GRB 010222 was found to be a steady source, suggesting the flux was dominated by emission from a bright host galaxy (Frail et al. 2002). Useful upper limits were also obtained for a number of other hosts (Galama et al. 1999; Kulkarni et al. 1999b; Smith et al. 1999, 2001).

It is possible to average a number of non-detections providing systematic uncertainties are small, to find the average flux density for a whole sample. Unfortunately in the case of the afterglow observations, since there may well be some small afterglow contribution to each observation, even if it is not detected significantly in individual cases, this averaging procedure is best avoided. For the data discussed here the observations were generally made long after the afterglow should have faded.

An obvious concern, already raised in Section 1.3, is that those GRBs with optically detected afterglows may be biased against residing in dusty hosts, the very galaxies which would on average be submm-bright. In an effort to assess whether such a bias exists, Barnard et al. (2003, hereafter paper 1) observed a small sample of 'dark' GRBs with deep limits on any optical afterglow but with good radio and/or X-ray positions. The expectation at the outset was that compared to the hosts of optically bright GRBs, these would be more likely to be dusty, massive star-forming galaxies. In fact, this sample of four produced only one individually significant detection, and no overall excess of 850-μm emission over that predicted by Ramirez-Ruiz et al. (2002) for all hosts.

These results appear to argue against dark bursts being preferentially found in dusty hosts. However, this is only a small sample, and in paper 1 we also remarked that there was some evidence from the rapid decay of the radio afterglows that two of the bursts in submm-faint hosts could have been dark due to intrinsic optical faintness, rather than extinction. In fact, it is becoming clearer that there is a broad range in brightness of optical afterglows and a number of detected bursts would have been missed in most afterglow searches. For example, GRB 980613, GRB 000630 and GRB 021211 (Fynbo et al. 2001; Hjorth et al. 2002; Fox et al. 2003) were all around $R \sim 23$ at 1 d, and, although the sample of bursts studied in paper 1 were fainter than all these, the upper limits do not require them to have been much fainter. Similarly, GRB 020124 had a relatively typical intrinsic magnitude, but appeared faint because of its redshift of $z = 3.2$ (Hjorth et al. 2003b). In any event, as we see below, even the modest rate of submm detections for dark-burst hosts found in paper 1 appears to be somewhat greater than the rate which is now found for hosts of optically detected bursts.

[1] http://www.mpe.mpg.de/$\sim$jcg/grbgen.html

Recently Berger et al. (2003, hereafter Be03) published SCUBA 850-μm measures for a larger sample of 13 GRB hosts, in addition to radio observations for many. Below we present our results for another sample of hosts (which partially overlaps with Be03), and combine and analyse all the extant data.

3 NEW DATA

We have obtained further submm photometry of the host galaxies of optically identified GRBs, using the Submillimetre Common User Bollometer Array (SCUBA) instrument on the James Clerk Maxwell Telescope (JCMT). The targets were chosen to be well placed for observation from Mauna Kea, and have subarcsec positions from their optical afterglows. All observations were made at least 12 weeks after the burst (and usually much longer), and are therefore very unlikely to be contaminated with afterglow emission.

Observations and reduction were performed as described in paper 1. The log and results are detailed in Table 1; note that some were reported by Barnard (2002). Of the galaxies presented here and in paper 1, seven are in common with Be03. This is useful to improve the measurement uncertainties, and also to check for statistical consistency, since the methods of reduction differ somewhat. Overall, we are reassured to find no significant systematic difference between the two data sets. The galaxy-to-galaxy scatter is, however, a little larger than expected from the quoted errors. Specifically, four of the seven disagree by more than 1σ, which could happen by chance, but it leads us to suspect that the uncertainties found by one or both groups are marginally underestimated.

Table 1. 850-μm photometry observations of a new sample of GRB hosts, chosen on the basis of good positions easily observable from Mauna Kea. Note the varying number of integrations per target – the quoted flux densities are error-weighted averages of the measurements for each source. The $\tau_{850\ \mu\mathrm{m}}$ measures the sky opacity during the observations. As can be seen, we do not enforce positivity on the submm fluxes, so as not to bias any subsequent statistical analysis. In a few cases the uncertainties are still large, and the data of limited use, but we report them here for completeness.

GRB	Obs. date	Int. (s)	$\tau_{850\ \mu\mathrm{m}}$	Flux density (mJy)
970228	23 Sep 02	2700	0.30	1.78 ± 1.32
	26 Dec 02	1350	0.14	
980326	24 Mar 02	1800	0.28	−0.27 ± 1.18
	23 Sep 02	2700	0.30	
	28 Dec 02	1350	0.09	
980329	31 Mar 02	450	0.33	−1.53 ± 1.19
	20 Sep 02	900	0.32	
	22 Sep 02	1800	0.25	
	03 Oct 02	1350	0.33	
	23 Dec 02	1350	0.17	
980703	22 Sep 02	1350	0.22	−1.36 ± 1.14
	23 Sep 02	1350	0.28	
990123	21 Apr 02	450	0.35	−4.18 ± 4.55
990308	30 Mar 02	324	0.25	0.02 ± 1.75
	08 Dec 02	1350	0.12	
991208	22 Mar 02	3330	0.16	1.97 ± 1.22
000301C	21 Mar 02	4050	0.20	−1.81 ± 1.21
000926	22 Mar 02	1350	0.16	1.40 ± 1.23
	30 Mar 02	675	0.15	
	26 Apr 02	2250	0.19	
001025A*	05 Oct 01	2250	0.30	−2.53 ± 3.04
010921	26 Apr 02	2502	0.20	0.46 ± 1.14
	23 Sep 02	2700	0.30	
	10 Dec 02	450	0.12	
011211	12 Mar 02	1260	0.40	3.81 ± 1.87
	19 Mar 02	2700	0.32	
020124	02 Jan 03	1350	0.26	1.20 ± 2.30
020813	30 Dec 02	1350	0.22	−1.40 ± 3.50
021004	29 Dec 02	2250	0.14	0.77 ± 1.25
	30 Dec 02	1350	0.22	

*The position of GRB 001025A was first observed as part of the dark-burst programme reported in paper 1, but was subsequently rejected because of doubts over the validity of the X-ray afterglow identification. More recently the original identification has been confirmed (Watson et al. 2002), so we report this submm measurement here.

In Table 2, we combine these results with the data presented in paper 1 and Be03. Where galaxies have been observed twice, we average using weights derived from the quoted errors. In one case, GRB 000911, Smith et al. (2001) find a flux which is inconsistent with Be03, and we therefore average those results together. In another case, GRB 990123, the limits from Galama et al. (1999) and Kulkarni et al. (1999b) on afterglow emission are a considerably stronger constraint on any host contribution than our photometry, so again we adopt an average value. Although strictly this could introduce afterglow contamination it must be very small.

4 DISCUSSION

The combined sample contains 21 host galaxies which have 850-μm measures with better than 1.4-mJy uncertainties; indeed most of these have errors $\lesssim 1$ mJy. Our discussion refers mainly to this well-observed sample.

Only three galaxies have significant positive detections, namely the hosts of GRB 010222, GRB 000418 and GRB 000210, which are all found at $>3.5\sigma$, and so can be regarded as confident detections. A few others have $\sim 2\sigma$ detections, but we should be more wary of these, particularly since there are also a couple of cases of $\sim 2\sigma$ negative fluxes. This latter fact could be taken as a further hint of a small underestimate in the errors, but equally it could be a chance occurrence given the sample size and the fact that the quoted errors do not account for crowding noise.

For reasonable dust temperatures of order 40 K, corresponding to rest-frame far-IR SEDs peaking at about 90 μm, the luminosities of these galaxies would be about $6 \times 10^{12}\ \mathrm{L}_{\odot}$. If all this energy was provided by star formation, then a star formation rate upward of 1000 $\mathrm{M}_{\odot}\ \mathrm{yr}^{-1}$ would be required (e.g. Blain et al. 2003).

Two hosts previously identified as possibly highly star forming are GRB 980703 and GRB 000911, on the basis of radio flux (Berger et al. 2001b) and submm (Be03) respectively. Our compilation suggests that in both instances these initial results were overestimates – in the former case, plausibly due to the scatter in the FIR-radio correlation. In the case of GRB 000911, the conclusion proceeds from the low flux seen in the afterglow observations of Smith et al. (2001). As a general point, we note that when working at the limit of detection, since there are many more low-luminosity galaxies than high-luminosity, the fluxes of the brightest galaxies in any sample are more likely to be overestimates than underestimates. This effect is akin to Eddington–Malmquist bias, and tells us that we should not be surprised if the fluxes of the brighter galaxies are frequently found to be lower on remeasurement.

4.1 Properties of the sample

For these 21 hosts, the error-weighted mean 850-μm flux density is 0.93 ± 0.18 mJy. This can be used to test the null hypothesis of zero flux for the sample, and, as expected, rejects it with confidence. However, this number is not a fair estimate of the true mean of the sample since we have not accounted for the intrinsic dispersion in

Table 2. Compilation of GRB hosts with submm observations from our programme and Berger et al. (2003). The fluxes are weighted means of the available photometry. Most of these galaxies are not detected significantly in their own right and, as expected, some formally have negative fluxes, simply due to noise. Redshifts and magnitudes of host galaxies have been obtained from the literature, with the latter being converted to the Cousins *R* system where necessary and corrected for foreground extinction according to the Schlegel, Finkbeiner & Davis (1998) maps.

GRB host	Redshift	Host R_C mag.	850-μm flux density (mJy)	Notes and references
970228	0.70	24.6	0.20 ± 0.81	Bloom, Djorgovski & Kulkarni (2001); Fruchter et al. (1999a); Galama et al. (2000)
970508	0.84	25.1	-1.57 ± 1.01	Metzger et al. (1997), Fruchter et al. (2000b)
970828	0.96	25.1	1.26 ± 2.36	Dark; Djorgovski et al. (2001)
971214	3.42	25.6	0.49 ± 1.11	Kulkarni et al. (1998)
980326	?	27.9	-0.27 ± 1.18	Bloom et al. (1998); Fruchter, Vreeswijk & Nugent (2001)
980329	?	26.3	0.71 ± 0.69	Jaunsen et al. (2003)
980613	1.10	23.9	1.75 ± 0.92	Djorgovski, Bloom & Kulkarni (2003); Hjorth et al. (2002)
980703	0.97	22.6	-1.53 ± 0.72	Djorgovski et al. (1998), Holland et al. (2001)
981226	?	24.8	-2.79 ± 1.17	Dark; Frail et al. (1999)
990123*	1.60	23.9	0.47 ± 0.60	Bloom et al. (1999); Kulkarni et al. (1999a); Fruchter et al. (1999b)
990308	?	29.6	0.02 ± 1.75	Jaunsen et al. (2003)
990506	1.31	25.5	-0.25 ± 1.36	Dark; Bloom et al. (2003); Le Floc'h et al. (2003)
991208	0.71	24.2	0.34 ± 0.83	Castro-Tirado et al. (2001), Fruchter et al. (2000b)
991216	1.02	25.2	0.47 ± 0.94	Vreeswijk et al. (1999, 2000)
000210	0.85	23.5	3.05 ± 0.76	Dark; Piro et al. (2002)
000301C	2.03	27.9	-1.46 ± 0.90	Smette et al. (2001); Fruchter & Vreeswijk (2001); Jensen et al. (2001)
000418	1.12	23.8	3.15 ± 0.90	Bloom et al. (2003); Klose et al. (2000); Metzger et al. (2000)
000911†	1.06	25.1	1.11 ± 0.63	Price et al. (2002b)
000926	2.04	24.8	1.40 ± 1.23	Castro et al. (2003); Fynbo et al. (2000); Rol et al. (2000)
001025A	?	24.0	-2.53 ± 3.04	Dark; Pedersen et al., in preparation
010222	1.48	25.7	3.74 ± 0.53	Jha et al. (2001); Fruchter et al. (2001a); Galama et al. (2003)
010921	0.45	21.5	0.46 ± 1.14	Price et al. (2002a), Park et al. (2002)
011211	2.14	24.8	1.94 ± 0.89	Fruchter et al. (2001b); Holland et al. (2002); Jakobsson et al. (2003)
020124	3.20	>29.5	1.20 ± 2.30	Hjorth et al. (2003), Berger et al. (2002)
020813	1.25	24.2	-1.40 ± 3.50	Barth et al. (2003); Castro Cerón et al., in preparation
021004	2.32	24.3	0.77 ± 1.25	Møller et al. (2002), Chornock & Filipenko (2002); Fynbo et al., in preparation

*GRB 990123 was observed by Galama et al. (1999) and Kulkarni et al. (1999b) with SCUBA (850 μm) on several occasions between 1 and 15 days after the burst. Although there is the possibility of a small amount of afterglow contamination, the flux density we list here is an weighted average of all the Galama et al. and Kulkarni et al. measures, together with our rather shallow result. For the purpose of the analysis presented here, the fact that a host flux density of >2 mJy is ruled out is the important point. † The GRB 000911 host was observed by Be03 at 2.31 ± 0.91 mJy and also by Smith et al. (2001) who found 0.03 ± 0.86 mJy about a week after the burst. Since this is the one case of a significant discrepancy between the Smith et al. result and a subsequent measurement, we have chosen to average the two results here.

GRB host-galaxy luminosities (about which we do not have prior knowledge), and also because the brighter galaxies were in some cases (notably GRB 010222) observed for longer and hence have smaller error bars for that reason. The unweighted mean is 0.58 ± 0.36 mJy, and is a fairer estimate of the true mean. This is higher than the average 850-μm flux density found for samples of Lyman-break galaxies, which range between 0 and ~0.4 mJy, depending on the exact sample selection (Chapman et al. 2000; Peacock et al. 2000; Webb et al. 2003).

What distribution do we expect to see? As a starting point, we assume that both submm luminosity and GRB rate are perfectly correlated with star formation rate. In that case, if submm flux and GRB detection completeness were also perfectly redshift independent, then the predicted distribution would simply be the submm-luminosity-weighted luminosity function of all galaxies.

Ramirez-Ruiz et al. (2002) use the models of Blain et al. (1999a,b) for the evolution of the submm galaxy population to predict the 850-μm flux density distribution of GRB hosts. Uncertainties in the model are almost entirely due to the uncertain link between the GRB rate and high-mass star formation heating dust. Subject to the, probably low, rate of contamination in the submm galaxy population from AGN heating, and to possible evolution of the initial mass function (IMF), the flux density distribution of submm galaxies is reasonably well constrained throughout the interval 1–15 mJy (Blain et al. 2002; Borys et al. 2003). Although it predates the substantially complete observed redshift distribution of submm galaxies from Chapman et al. (2003a), the assumed model is in good agreement with these results. It is possible that the galaxies are systematically cooler and less luminous (e.g. Efstathiou & Rowan-Robinson 2003); however, if that is the case, then the redshift distribution is only consistent with significant evolution of the form of the far-infrared–radio correlation with redshift.

Fig. 1 shows the predictions of this model as filled points. To provide a fair comparison, the model output was convolved with the distribution of observational errors, and includes a correction to allow for the possibility of the chance appearance of an unrelated submm source in the SCUBA beam. The latter correction amounts to roughly 0.7 of an object contaminating the 2–4 mJy bin and is based on the source counts summarized in Blain et al. (2002). We have chosen to put error bars on the model, reflecting the counting statistics of the proportion expected in each bin. The histogram represents the submm observations.

It is apparent that there is a dearth of hosts with >4-mJy, 850-μm flux densities, which is becoming statistically significant (formally, at the 1.6σ level). In fact, the significance is greater if we consider the remaining five galaxies with larger error bars, namely GRB 970828, GRB 990308, GRB 001025A, GRB 020124 and GRB 020813 (and

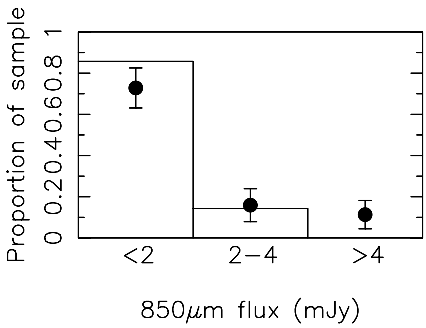

Figure 1. Comparison between observations (histogram) for the 21 hosts with <1.4-mJy flux uncertainties, and predictions (shown as filled points). The results are binned into just three (different sized) bins, essentially representing no confident detection, confident but faint detection, and 'bright' detection respectively. The predictions are based on those from Ramirez-Ruiz et al. (2002) but also account for the observational error distribution and the crowding noise (i.e. essentially the rate of false positives). Errors bars are placed on the predictions simply reflecting the counting statistics rather than any uncertainty in the model parameters. In that sense, they are a lower limit to the true errors.

indeed one might also include GRB 980519 from Smith et al. 1999), since at 1σ these are all inconsistent with being >4-mJy sources as well.

Furthermore, we note that if the estimated flux uncertainties are somewhat optimistic (as suggested in Section 3), it tends to make the discrepancy between theory and observations rather worse. This seems counterintuitive, but is due to the fact that larger observational errors should result in more low-luminosity systems appearing in the brighter bins by chance.

At this stage there are many possible explanations for the discrepancy (beyond the relatively small sample size). First and foremost, we must still worry that amongst the GRBs with 'very dark' afterglows, for which good radio or X-ray positions are not available, lurk a small number of highly submm-luminous hosts. Another potential selection effect is that GRBs are being preferentially picked up at lower redshifts, both in terms of initial detection, but more significantly the detection of the afterglows, as discussed in Section 1.3. This would be a less direct selection against the higher redshift, dusty systems, although we note that of the seven systems with $z > 1.5$, *none* have significant 850-μm fluxes.

Other possible physical explanations are as follows.

(i) GRBs are preferentially found in low-metallicity – smaller and less dusty – systems. This has been predicted as a consequence of the single-star collapsar model (Heger et al. 2003), and is consistent with the apparent enhanced brightness of GRBs in the outer parts of their parent galaxies (Ramirez-Ruiz, Lazzati & Blain 2002), and the relatively low metallicity inferred for many GRB hosts (e.g. Fynbo et al. 2003). The latter study notes that a large proportion of GRB hosts are Lyα emitters (five out of five so far studied), which is significantly greater than the proportion of Lyman-break galaxies, although perhaps surprisingly, many of the SCUBA galaxies for which Chapman et al. have recently acquired redshifts are also strong Lyα emitters.

(ii) The higher-luminosity submm galaxies are more contaminated by AGN, or the submm luminosity function more contaminated by cooler, less luminous galaxies, than has been generally thought.

(iii) While both GRBs and submm flux trace star formation rate, the two are not perfectly correlated due to different phase lags with respect to the true star formation rate. For instance, the simulation of Bekki & Shioya (2001) of a merger-induced starburst shows significant fluctuations in the star formation rate on time-scales much less than 100 Myr (their fig. 6). Given that both GRB rate and submm flux will not follow rapid fluctuations instantaneously, some decorrelation may occur.

(iv) Variations in the stellar IMF are having a different effect on GRB rate compared to submm flux; or (e) that GRBs for some reason are occurring preferentially in galaxies with high dust temperatures, so more of the bolometric luminosity appears at shorter wavelengths and is being missed at 850 μm.

4.2 Properties of the submm-bright GRB hosts

If submm flux traces star formation, and the selection of GRB hosts is unbiased, then the submm-bright GRB hosts as a whole should be similar to the general population of submm-bright galaxies. Of course, now we are dealing with a very small sample, but it is interesting to examine the properties of the three hosts with 850-μm flux densities above 2 mJy.

Gorosabel et al. (2003a) have constructed a UV to IR SED for the host to GRB 000210, which is well fitted by a starburst SED with a relatively modest star formation rate of 2 $\mathrm{M_{\odot}\,yr^{-1}}$ and negligible extinction. The redshift is $z = 0.84$ and the luminosity $L \approx 0.5L_{\star}$.

The UV to IR SED of the GRB 000418 host (Gorosabel et al. 2003b) is also well fitted by a starburst template, in this case with a moderate amount of extinction $A_V \sim 0.4$, and a star formation rate up to 60 $\mathrm{M_{\odot}\,yr^{-1}}$. A similar result is obtained in the spectroscopic study of Bloom et al. (2003), who also find no evidence of any AGN contamination. This star formation rate is still an order of magnitude less than that derived from the submm, but that is not unreasonable for heavily obscured galaxies. The redshift is $z = 1.12$ and the luminosity is $L \approx L_{\star}$. It is compact with effective radius $r_{\mathrm{E}} \approx$ 1 kpc, and the afterglow was located close to the optical centroid (Fruchter & Metzger 2001; Bloom et al. 2003). The afterglow itself has produced extinction estimates ranging from $A_V \sim 0.4$ (Berger et al. 2001a) to $A_V \sim 1$ (Klose et al. 2000).

The host of GRB 010222 is fainter still in the optical at $R \approx 25.3$ (Fruchter et al. 2001a), but it is also moderately blue, with $I - K \approx$ 2.1 and an intrinsic luminosity $L \sim 0.1L_{\star}$ (Frail et al. 2002). The redshift is $z = 1.477$ and again *HST* images reveal the afterglow to have been located on top of the peak of the optical emission.

In all these cases if the submm is really indicating copious amounts of hidden star formation activity, it would appear that the optically visible part of the host is dominated by one or more relatively unextinguished regions. This is plausible – it could be concentrated in a shell or plume of material, or possibly a number of 'windows' through an obscuring shroud (e.g. Bekki, Shioya & Tanaka 1999). However, if this is the case, it also seems that the optically bright regions must be spatially proximate to the bright far-IR emission if we are to understand why the afterglows (as with most detected GRBs) tend to be found close to the optical centroids (or hotspots) of the hosts.

So, how do the properties of these galaxies compare with the the optical/IR counterparts of the submm-bright galaxies selected in blank-field SCUBA surveys? In fact the bright SCUBA galaxies display quite a wide variety of characteristics. They have been split into three classes (Smail et al. 2002): class 0 are relatively bright in optical as well as submm – much of the star formation is unextinguished; class 1 are extremely red objects (EROs) with $I - K$ typically greater than 5; finally class 2 are extremely faint in optical and IR. This classification system was conceived based on galaxies which are generally brighter than 5 mJy at 850 μm. Although no GRB host to-date is that bright, it appears that the submm-brightest of the GRB hosts do not fit neatly into this scheme, being intermediate in optical/IR luminosity between classes 0 and 2, but not very red EROs like class 1. Interestingly, the best candidate for an extremely red GRB host galaxy, that of GRB 980326 which has $R-K \gtrsim 6$ (although the K detection at $K = 22.9$ is $<3\sigma$; Chary, Becklin & Armus 2002), has a low submm luminosity. This compares to an average 850-μm flux density of ≈ 1.6 mJy recently found by Wehner, Barger & Kneib (2002) for a K-selected sample of EROs.

Furthermore, as discussed in Section 1.2, the redshift distribution of bright SCUBA sources shows a peak in the redshift range 2–3, whereas these three submm-bright GRB hosts are nearer $z \sim 1$.

We conclude that the properties of the few submm-bright GRB hosts found to-date are not very representative of the submm-bright galaxies as a whole: they do not fit easily within any of the three classes. Be03 reached the same conclusion based on a colour–redshift plot, in which the submm-bright GRB hosts lie bluer and at lower redshift than the submm-selected galaxies as a whole. This could be because the GRB hosts are somewhat fainter at 850 μm, since nearly all well-studied submm samples are $\gtrsim$5 mJy (although Frayer et al. 2003 report a detailed study of a single gravitationally lensed source at $z = 2.51$, which has a low submm flux density of $S_{850} < 2$ mJy after correction for lensing). As discussed above, we also expect GRB selection to provide some bias toward picking up lower-redshift galaxies, and against very dusty galaxies. The alternative, of course, is that either the submm selection has some problems, such as a surprising rate of AGN contamination, or surprising dust properties, or GRB progenitors are more likely to arise in less dusty systems.

5 CONCLUSIONS

We have shown that while a small number of GRB hosts are bright submm galaxies, indicating high star formation rates, the proportion, particularly at flux densities >4 mJy, is fewer than predicted if both GRBs and submm flux trace star formation in an unbiased way. Furthermore, and similarly puzzling, the three submm-brightest GRB hosts are not very typical in terms of their optical properties and redshift distribution of the galaxies selected in blind submm surveys.

Of course, the current sample size is still rather small, and very likely suffers some selection biases. In particular, GRBs in very dusty hosts and/or at higher redshifts are more likely to be missing from the observed afterglow samples. A small number of these amongst the 'dark' bursts (those without optical counterparts to deep limits) could remove the discrepancy – although the afterglows known to be genuinely very faint is only a small fraction of those for which optical emission has not been detected. Furthermore, a fair proportion of the darker bursts seem to be dark for reasons other than their residing in high-redshift, dusty ULIRGs, so it is not obvious that this selection effect provides the full explanation.

Future studies may largely overcome these selection problems by much earlier and more uniform afterglow searches with *SWIFT* and various robotic telescopes. The positions from the *SWIFT*/XRT may be good enough to identify ULIRG hosts, even when no optical afterglow is detected. *Spitzer* will also be a powerful tool, particularly for the lower-redshift hosts $z \lesssim 1$, where the large majority of the bolometric luminosity appears in the far-IR.

If it turns out that the discrepancy with the model predictions persists when more complete samples are studied, it will certainly be telling us something interesting about the astrophysics of GRBs and/or the relationship between FIR emission and star formation. On the other hand, if the disagreement goes away, the use of GRBs as practical star formation indicators will be strongly bolstered.

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