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SCUBA observations of the host galaxies of four dark gamma-ray bursts

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ABSTRACT

We present the results of a search for submillimetre-luminous host galaxies of optically dark gamma-ray bursts (GRBs) using the Submillimetre Common-User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT). We made photometry measurements of the 850- μm flux at the location of four 'dark bursts', which are those with no detected optical afterglow despite rapid deep searches, and which may therefore be within galaxies containing substantial amounts of dust. We were unable to detect any individual source significantly. Our results are consistent with predictions for the host galaxy population as a whole, rather than for a subset of dusty hosts. This indicates that optically dark GRBs are not especially associated with very submillimetre-luminous galaxies and so cannot be used as reliable indicators of dust-enshrouded massive star formation activity. Further observations are required to establish the relationship between the wider GRB host galaxy population and SCUBA galaxies.

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

1 INTRODUCTION

1.1 Gamma-ray bursts

It is generally now accepted that the afterglow emission resulting from (long-duration, soft-spectrum) gamma-ray bursts (GRBs) can be explained by an ultra-relativistic shock wave expanding into a surrounding medium (Mészáros & Rees 1997; van Paradijs, Kouveliotou & Wijers 2000; Mészáros 2001). The precise nature of the progenitor systems is not a settled issue. The two most popular theories both involve stellar remnants: the collapsar/hypernova model, in which a single massive progenitor star undergoes core collapse (Woosley 1993; Paczyński 1998); and the binary merger theory, in which two massive stellar remnants, such as neutron stars, merge (Lattimer & Schramm 1976; Paczyński 1986). Both of these scenarios may be able to explain the energetics of the explosion that produces the GRBs, particularly if they are beamed, since the ener-

gies of GRBs are comparable to those involved in the formation of typical stellar-progenitor black holes.

Recently, the collapsar/hypernova model has gained support from three sets of observations: first, it was confirmed that the positions of some GRBs accurately localized by the observation of optical and/or radio afterglows, were found to be within star-forming regions of their host galaxies (Bloom, Kulkarni & Djorgovski 2002), which themselves are frequently starburst galaxies (Sokolov et al. 2001). This is supported by X-ray determinations of the H I column density along the line of sight to GRBs, which is consistent with their residing in giant molecular clouds (Galama & Wijers 2001). During their creation, it is likely that the massive stellar remnants required in the binary merger scenario would receive a substantial 'kick' velocity, so that the merger event causing the GRB would take place outside the star-forming region of the host galaxy (Galama & Wijers 2001). Also, the delay required between formation of the remnants and their merger may well be long enough for star formation to have ceased in the host, suggesting that the host galaxy would no longer be luminous. Hence the position measurements of Bloom et al. (2002) support the single massive progenitor theory.

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Note, though, that one should be wary of a potential selection effect: the detection of a GRB afterglow requires a certain minimum density in the surrounding interstellar medium (ISM), and so GRBs may only be identifiable when they occur inside galaxies (Chevalier & Li 2000).

Secondly, in a few cases, optical afterglows of GRBs have been seen to contain a secondary brightening in flux after a few weeks (Kulkarni et al. 1998; Bloom et al. 1999; Reichart 1999; Galama et al. 2000; Lazzati et al. 2001). This flux increase, although often not very significant, has been attributed to a supernova occurring simultaneously with the GRB, although alternative ideas have been postulated, such as dust echoes (Esin & Blandford 2000) or interactions of the GRB shock wave with wind-driven density structures in the surrounding ISM (Ramirez-Ruiz et al. 2001). Supernovae associated with GRBs are compatible with the single progenitor collapsar/hypernova model rather than the merger hypothesis.

Finally, the detection of iron features in the X-ray afterglows suggests the presence of an iron-enriched ISM surrounding the GRB progenitor (Amati et al. 2000; Piro et al. 2000; Yoshida et al. 2001). This high iron mass is consistent with ejecta from a massive stellar progenitor.

If the hypernova theory is the correct explanation for long-duration GRBs, then there should be a direct link between GRBs and high-mass star formation activity. Since the gamma-ray emission from the initial explosion is not attenuated by dust, and can be detected from high redshifts, GRBs should be unbiased tracers pointing to star formation activity wherever massive stars are living and dying (Krumholz, Thorsett & Harrison 1998; Blain & Natarajan 2000; Berger et al. 2001b; Frail et al. 2002; Ramirez-Ruiz, Trentham & Blain 2002).

1.2 SCUBA galaxies

Since the commissioning of the SCUBA instrument (Holland et al. 1999) in 1997 on the James Clerk Maxwell Telescope (JCMT) on Mauna Kea, a new era of submillimetre cosmology has been possible (see e.g. Blain et al. 1999a; Smail et al. 2002). In particular, the discovery of a substantial population of dust-enshrouded ‘SCUBA galaxies’ has launched a debate regarding observational estimates of the global star formation rate in the Universe. SCUBA traces the interstellar dust in galaxies (with a temperature of the order of tens of degrees kelvin), which may be heated by the ultraviolet light emitted by OB stars and/or a hosted active galactic nucleus (AGN). The relative contributions of starlight and AGN to dust heating in a particular galaxy are hard to determine precisely, but studies using *Chandra* to observe hard X-rays from submillimetre-selected galaxies suggest that about 20 per cent of the sample contain a detectable AGN (Bautz et al. 2000; Fabian et al. 2000; Almaini et al. 2001).

Therefore it is likely that the luminous dust emission from SCUBA galaxies is powered predominantly by star formation. In this case, because of the large bolometric luminosities of the SCUBA galaxies (at least $10^{12} L_{\odot}$), they make a substantial contribution to overall star formation activity in the high-redshift Universe, comparable to or greater than that of optically selected galaxies (Blain et al. 1999a). Thus they are good candidates to be hosts of many GRBs, if GRBs are indeed associated with the death of high-mass stars. The optical properties of SCUBA galaxies, where they are well-located, indicate that most are very faint, with $R > 25$ (Smail et al. 2002), not dissimilar to the GRB host galaxy population as a whole (Djorgovski et al. 2001). It is likely that about 10–20 per cent

of the star formation activity in the high-redshift Universe takes place in submillimetre galaxies brighter than 2 mJy. As a result, perhaps one in five GRBs should reside in such objects. This point is examined further in Section 4.

1.3 Submillimetre observations of GRBs

This paper describes our submillimetre SCUBA observations of the host galaxies of four GRBs. To increase the chances of finding dusty SCUBA galaxies in this pilot programme, we selected GRBs that were ‘dark’ in the sense that their afterglows were undetected in the optical despite deep, rapid searches. Estimates vary, but optical afterglows have been searched for and not found in roughly 30–50 per cent of GRBs with X-ray afterglows. In many cases the non-detection may simply be because the searches were not deep or rapid enough (Galama & Wijers 2001), but in some instances it is clear that the optical afterglows are genuinely underluminous (Groot et al. 1998; van Paradijs et al. 2000; Lazzati, Covino & Ghisellini 2002; Ramirez-Ruiz et al. 2002). An obvious possibility is that these bursts are heavily obscured by dust. Since GRBs are expected to destroy any dust in their vicinity (Waxman & Draine 2000; Fruchter, Krolik & Rhoads 2001; Reichart & Yost 2001; Venemans & Blain 2001), the obscuration would have to be due to dust elsewhere along the line of sight, as might well be expected in very dusty submillimetre-bright galaxies.

Note that we did not attempt to observe GRB afterglows in the submillimetre. Target of Opportunity programmes to observe GRB afterglows are underway at the JCMT and IRAM 30-m telescopes (Smith et al. 1999, 2001; Frail et al. 2002). Our observations took place long enough after the initial explosion for only the host galaxy emission to be detectable.

There have been two previous SCUBA detections of a GRB host galaxy. The first was found serendipitously during a submillimetre afterglow search (Frail et al. 2002) for a GRB that had an optical afterglow (GRB 010222). This suggests that the GRB was located in a luminous dusty galaxy, but either in a relatively dust-free region or near the edge of the galaxy, so that the explosion could clear out any dust along the line of sight. Also, Berger et al. (2001b) reported the results of a successful targeted search for submillimetre emission from GRB 000418. This too had an optical transient identification. Another relevant detection was that of a GRB host in the radio (GRB 980703; Berger, Kulkarni & Frail 2001a), the flux of which was claimed to be caused by a large star formation rate rather than AGN activity, based on optical spectroscopy and the absence of radio variability. However, a deeply embedded AGN within a dust- and gas-rich galaxy could plausibly contribute the emission from this galaxy, especially as the radio source is located very near to the nucleus of the host galaxy.

2 OBSERVATIONS

Observations were made using the 850- μm photometry pixel on the SCUBA array (Holland et al. 1999). They are summarized in Table 1. Simultaneous observations were made with the 450- μm photometry pixel, but weather conditions and/or array noise were never good enough to yield useful data. Observations were made in the standard photometry mode, using a 7-Hz, 60-arcsec ‘chop’ in azimuth to provide a blank-sky reference and a further telescope ‘nod’ to produce a measure of any sky gradient. Each set of photometry observations takes 18 s. Column 3 of Table 1 shows the integration time on-source for each GRB. Pointing was checked regularly and was always better than 2.5 arcsec, much smaller than

Table 1. Log of photometry observations. See notes about GRBs 001025 and 001109 in Section 2.

Source name	Date of obs.	Integ. time (s)	$\tau_{850\mu\text{m}}$
GRB 970828	24/04/01	900	0.23
GRB 981226	03/10/01	2052	0.27
	24/11/01	2115	0.27
GRB 990506	08/05/01	2250	0.26
GRB 000210	01/09/01	1800	0.24
	03/10/01	2250	0.27
GRB 001025	05/10/01	2250	0.30
GRB 001109	08/05/01	1350	0.26
	03/10/01	2700	0.26

the primary beam of the array of 14 arcsec at 850 μm . Seeing was monitored, especially around dawn and dusk, and data were only taken when the seeing was less than 1 arcsec. Sky transparency was calculated by interpolating between regular skydip values, although the situation was monitored more frequently with data from the water vapour monitor of the JCMT. The average sky opacity at 850 μm during the observations of each source, $\tau_{850\mu\text{m}}$, is given in column 4 of Table 1. For flux calibration, identical observations were made of the planets Mars and Uranus, and where necessary the secondary flux calibrator CRL 618. We found no significant deviations between the observed and expected fluxes of these standard objects.

Unfortunately, since the observations were made, two of the GRBs in our sample have been found to have been wrongly located: GRBs 001109 and 001025. In the case of GRB 001109, the radio-located position which we observed is now thought to correspond to a faint constant radio source (Berger & Frail 2001), and thus to be a mis-identification of the GRB afterglow. We detected a net positive flux of 1.89 ± 1.40 mJy from this source, consistent with its likely identification as a high-redshift star-forming galaxy (Berger & Frail 2001). For GRB 001025, *XMM* error box S1 was observed, since it contained a candidate host galaxy (Hjorth, private communication), but subsequently Hurley (private communication) has calculated that this error box lies outside a revised *Inter-planetary Network* annulus. Hence the results of the observations of both these objects are not included in the rest of this paper.

3 DATA REDUCTION

The data were reduced using the standard Starlink SURF procedures (Jenness & Lightfoot 2000). Particular care was taken over the removal of atmospheric noise, since the expected low fluxes of the sources make this an important factor. This sky-noise removal is possible using the other bolometers on the array, assuming that they are pointing at the blank sky. Following Isaak et al. (2002), the median value of the signal from the reference bolometers was used rather than the mean. Usually the reference bolometers used are the inner ring on the 850- μm array. For the 2001 October observations (see Table 1), however, the whole array suffered from elevated noise. Particular care was taken to choose only those bolometers with normal noise levels for this final sky-removal stage, and the bolometer noise values were measured far more frequently than usual. The results presented have been clipped at the 3σ level, although this generally had little effect on the final results.

Table 2. Coadded 850- μm results for the four objects observed. Redshifts z and R magnitudes, where determined, for candidate host galaxies are shown here [Djorgovski et al. 2001 (GRB 970828), Holland et al. 2000 (GRB 981226), Bloom, Frail & Sari 2001 (GRB 990506) and Piro et al. 2002 (GRB 000210)].

Source	Flux (mJy)	z	R mag
GRB 970828	1.26 ± 2.36	0.96	25.5
GRB 981226	-2.79 ± 1.17	–	24.3
GRB 990506	-0.25 ± 1.36	1.3	24.8
GRB 000210	3.31 ± 1.54	0.85	23.5

4 RESULTS AND DISCUSSION

Table 2 shows the overall weighted mean at 850 μm for each of the four reliable sources observed. The overall, weighted mean flux for all four sources is -0.37 ± 0.82 mJy.

Models for the evolution of the star formation rate in dusty galaxies can be used to predict the likely 850- μm fluxes of GRB hosts (Blain et al. 1999a,b; Blain & Natarajan 2000; Ramirez-Ruiz et al. 2002), as shown in Fig. 1. We assume the following: that dust in SCUBA galaxies is predominantly heated by high-mass stars; that GRB rates are tied to the rate of formation of high-mass stars; and that most high-redshift star formation activity is enshrouded by dust. Results for two models based on infrared and submillimetre data are presented: a simple parametric model of the evolution of low-redshift galaxies (BSIK: Blain et al. 1999a) and a model based on luminous hierarchical merging of galaxies (BJS�KI: Blain et al.

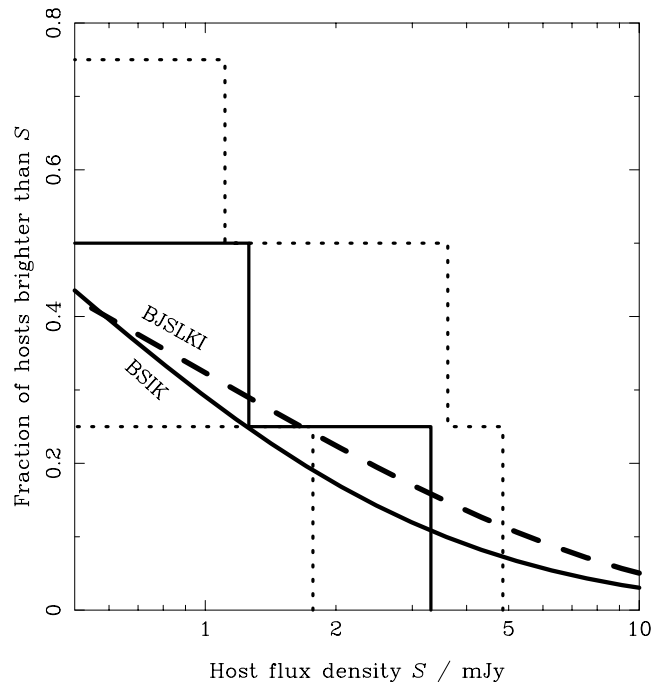


Figure 1. Comparison between results and predictions (Ramirez-Ruiz et al. 2002). The smooth curves show the fraction of all GRB host galaxies expected to exceed a given 850- μm flux in two current models – for a pure luminosity evolution (BSIK: Blain et al. 1999a) and an hierarchical model (BJS�KI: Blain et al. 1999b) respectively. Stepped lines show results from this pilot study – see text.

1999b). These models both provide a good representation of the evolution of dusty galaxies, measured in other observations. About 20 per cent of *all* GRB host galaxies are expected to have fluxes above the SCUBA confusion limit for detection of 2 mJy; about 10 per cent are expected to have fluxes greater than 5 mJy. In general, we predict an average across *all* sources of 0.9 mJy. The solid histogram shows the result of our observations, and the dotted histograms define the $\pm 1\sigma$ errors in flux.

It is clear from Fig. 1 that the errors on our results are consistent with the predictions of the galaxy evolution models, and that the overall mean flux is within 2σ of the expected value. GRB 000210 is clearly our best candidate for a detection, but only at a significance of about 2σ . However, observations of GRB 000210 suffered from the raised array noise discussed in Section 3, and from its low elevation from Mauna Kea. Hence the atmospheric noise for GRB 000210 was greater than for our other sources.

Note that we purposefully chose a selection bias that should have increased our chances of finding dusty GRB hosts, by observing ‘dark bursts’. Since we did not see any increase in our detection rate, alternative explanations are necessary for the lack of optical afterglow detections. We now look briefly at the four reliable GRBs in our sample in more depth.

4.1 Individual sources

4.1.1 GRB 981226

Three early candidates for the optical afterglow of GRB 981226 (Castro-Tirado et al. 1998; Galama et al. 1998; Wozniak et al. 1998) were rejected upon the location of a radio afterglow (Frail et al. 1999). The limit on the optical afterglow is therefore $R > 23.5$ at 10 h after the alert (Lindgren et al. 1998). Later *Hubble Space Telescope* (*HST*)/STIS and Very Large Array (VLA) imaging has located the probable host galaxy (Holland et al. 2000).

The multi-wavelength afterglow emission from GRB 981226 provides some clues. The X-ray afterglow was found to have a double-peaked structure followed by a rapid decay (Frontera et al. 2000). Also, Frail et al. (1999) noted a rapid decline in the radio afterglow. Taken together, the X-ray, optical and radio afterglow behaviour may all be explained by a complicated density structure in the ISM around the GRB. In particular, a cavity in the ISM density would explain the rapid X-ray and radio decays, and would predict a similarly fast optical decay, meaning that the optical afterglow searches were too slow/shallow to detect the emission. Such a structure could be produced by the mass-loss phases that massive stars (which are of course plausible GRB progenitors) are known to go through in their post-main-sequence lives (Chevalier & Li 2000; Ramirez-Ruiz et al. 2001). Hence there may be no need to infer the presence of dust around this GRB. Other suggestions for rapid decays have been proposed that also do not rely on the presence of dust, such as the effects of jet structure (Frail et al. 2001; Panaitescu & Kumar 2001).

Our non-detection is consistent with the brief weather-affected SCUBA afterglow search for this GRB by Smith et al. (1999).

4.1.2 GRB 990506

GRB 990506 appears to have some similarities to GRB 981226. Again it had a very rapidly decaying radio transient (Taylor et al. 2000). The optical transient was not detected at $R = 19$ after 1 h (Zhu & Zhang 1999), or to $R = 23.5$ after 11 h (Pedersen et al.

1999). The rapid decay of the radio afterglow again suggests that a non-dusty effect, local to the burst, may explain the absence of an optical afterglow. Optical searches for the host have identified it as a very faint and compact galaxy (Bloom et al. 2002).

4.1.3 GRB 970828

GRB 970828 was dark to a depth of $R = 23.8$ (Groot et al. 1998; Djorgovski et al. 2001) in observations taken from 4 h after the burst. A radio flash was observed by the VLA (Djorgovski et al. 2001) and has been interpreted as reverse shock emission. No conventional radio afterglow was detected. Subsequent Keck and *HST* observations of the location of the radio flare revealed an interacting three-component host (Djorgovski et al. 2001), with a possible identification of the GRB location in a dust lane between the two brightest components. In calculations considering both jet and spherical models for the GRB shock geometry, Djorgovski et al. (2001) conclude, based on the X-ray afterglow flux, that a single typical giant molecular cloud could provide all the extinction necessary to fit the upper limits to the optical afterglow flux density. They also note that the Keck and *HST* images indicate that the two host galaxy components on either side of the GRB location are both slightly but not highly reddened, suggesting a low total dust mass in the system.¹ Our positive but not significant measurement supports the hypothesis that, in this case at least, it was not galaxy-wide dust that caused the obscuration of the optical afterglow, but rather a localized cloud or clouds of dust along the line of sight, consistent with the X-ray results. Of course, the resolution of SCUBA is such that our observations are sensitive only to the total (illuminated) dust in the entire system.

4.1.4 GRB 000210

GRB 000210 represents our most likely host galaxy detection. Both X-ray and radio transients were found for this source, but no optical transient ($R > 23.5$ at 12.4 h after the burst: Gorosabel et al. 2002; Piro et al. 2002). The X-ray transient did not display the rapid decays found for GRBs 981226 and 990506, leading Piro et al. (2002) to reject the no-dust hypotheses discussed above. Instead they conclude that the most likely scenarios are either obscuration of the optical transient by a clumpy local environment, or line-of-sight obscuration by the whole host galaxy, either of which is allowed by our findings.

5 CONCLUSIONS

From our small sample of four reliably identified dark GRBs, we find that the ‘dark bursts’ do not preferentially select dusty host galaxies with very significant amounts of star formation. Looking at some members of our sample, we can explain the lack of optical transients in other ways. It seems likely that to characterize the optically dark bursts as a physically distinct population of GRBs would be misleading. In each case different circumstances arising from a combination of the observing conditions and the physical

¹ There are, however, indications from observations of galaxies known to be very luminous at submillimetre wavelengths (Ivison et al. 2001) that regions where dust emission is strong may not correlate with regions that at optical wavelengths appear to be reddened by strong extinction. Hence the lack of obvious extinction in optical images does not rule out the presence of a large amount of illuminated and heated dust.

conditions at the location of the GRB could give rise to the lack of an optical afterglow. If, instead, we view the GRBs included here as four examples of the overall population, we find that the results agree with the distribution predicted assuming that GRBs trace high-mass star formation. Our lack of a single strong detection implies that no more than 20 per cent of GRB hosts are submillimetre galaxies detectable at a flux density brighter than 5 mJy using SCUBA. In interpreting the results, however, the small sample size inevitably makes it hard to draw any solid conclusions.

Combining our three most significant results with the observations of Smith et al. (1999, 2001), we find that 11 GRB locations have been observed with SCUBA to noise levels < 2 mJy, and in all but two [GRB 980329 (Smith et al. (1999) and GRB 000210 (this paper)] detection of submillimetre emission from a host galaxy was ruled out. The two GRB hosts detected by SCUBA (Frail et al. 2002; Berger et al. 2001a) had afterglows with optical transients. Therefore, while some GRBs definitely are located in dusty galaxies, the route to selecting these GRBs on the basis of their afterglow data is not yet clear. Since GRBs can only clear dust out to less than a 100-pc distance (Fruchter et al. 2001), it would be surprising if optically selected samples of GRBs were not generally biased against dusty hosts.

However, as noted above, there may be alternative explanations for the optical faintness of some afterglows beyond location in a dusty host galaxy. Our results indicate that radio-located optically dark bursts seem not to be reliable indicators of luminous, dusty host galaxies. It may be that the physical conditions of the ISM in the densest star-forming regions are incompatible with the generation of intense radio emission from GRB shocks. In that regard, it would ultimately be interesting, and certainly possible in the *SWIFT* era, to study a sample of hosts of purely X-ray-selected GRBs, with the hope that the more prompt X-ray emission would be less affected by the wider environment of the progenitor.

From the SCUBA observations alone, we cannot separate the possibility that there is little dust in these systems from the possibility that there is a lot of dust but insufficient ultraviolet photons to make it glow brightly. Alternatively, the dust may be heated to high temperatures and so cannot be detected by SCUBA at all. The predicted flux of a $5 \times 10^{12} L_{\odot}$ galaxy at $z = 1$ decreases from 20 to 0.08 mJy as the dust temperature increases from 20 to 80 K (see fig. 5 in Blain et al. 2002). Typical dust temperatures for submillimetre-selected objects are thought to be 40 K (Ivison et al. 2000), but a temperature ~ 60 K would be hot enough to prevent such a galaxy being detected above the 2-mJy confusion limit of SCUBA. However, optical colours of the host galaxies of GRBs 970828, 981226 and 000210 (Frail et al. 1999; Djorgovski et al. 2001; Piro et al. 2002) show only modest reddening, to the optical depths that can be probed, and thus perhaps imply little dust overall in the hosts. Ideally, high-resolution observations to locate dust-enshrouded star formation activity with respect to the location of GRBs need to be made.

The results presented here suggest that a more extensive deep submillimetre survey of GRB hosts is necessary to investigate their far-infrared and submillimetre properties in detail, and this is now underway at the JCMT (Barnard et al., in preparation).

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