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Millimetric properties of gamma ray burst host galaxies

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ABSTRACT

We present millimetre (mm) and submillimetre (submm) photometry of a sample of five host galaxies of Gamma Ray Bursts (GRBs), obtained using the MAMBO2 and SCUBA bolometer arrays respectively. These observations were obtained as part of an ongoing project to investigate the status of GRBs as indicators of star formation. Our targets include two of the most unusual GRB host galaxies, selected as likely candidate submm galaxies: the extremely red ($R-K\approx 5$) host of GRB 030115, and the extremely faint ($R>29.5$) host of GRB 020124. Neither of these galaxies is detected, but the deep upper limits for GRB 030115 impose constraints on its spectral energy distribution, requiring a warmer dust temperature than is commonly adopted for submillimetre galaxies.

As a framework for interpreting these data, and for predicting the results of forthcoming submm surveys of *Swift*-derived host samples, we model the expected flux and redshift distributions based on luminosity functions of both submm galaxies and GRBs, assuming a direct proportionality between the GRB rate density and the global star formation rate density. We derive the effects of possible sources of uncertainty in these assumptions, including (1) introducing an anticorrelation between GRB rate and the global average metallicity, and (2) varying the dust temperature.

Key words: submillimetre – infrared: galaxies – dust, extinction – galaxies: evolution – cosmology: observations – gamma rays: bursts

1 INTRODUCTION

There is now strong evidence linking long-duration Gamma Ray Bursts (GRBs) with the core-collapse of massive stars (e.g. Hjorth et al. 2003a)— and hence, given the short main-sequence lifetimes of such stars, with star formation activity. Indeed, as tracers of star formation, GRBs hold a number of advantages over traditional methods. The high luminosity of their prompt emission and afterglows enable them to be detected, in principle, out to redshifts $\gtrsim$10 (in practice currently out to $z>6$, e.g. Haislip et al. 2006). Their high energy emission can furthermore pass unaffected through intervening gas and dust— the very conditions one would expect to be associated with massive star formation. As the outcome of a single stellar event, the luminosity of the GRB ought to be independent of that of its host galaxy, enabling localisation of galaxies too faint, dusty or distant to be detected by traditional means, thus sidestepping many of the biases that afflict optical and submm surveys. Furthermore, spectroscopy of the bright optical afterglows enables one to measure the redshift and other properties of the host galaxy, even when direct detection of the galaxy may be infeasible (e.g. Berger et al. 2002).

Once the star-forming properties of a carefully-selected subsample of GRB hosts have been established, it should be possible to derive the the star formation history of the Universe, by measuring the redshift distribution of GRBs. A purely GRB-selected galaxy sample should, furthermore, represent an unbiased census of the galaxy types reflecting their relative contribution to the bulk star formation rate. Hitherto it has been difficult to assess the biases afflicting the assembly of such samples, factors modulating the GRB

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rate as a function of redshift (for example, redshift dependence of density of surrounding medium; metallicity; stellar initial mass function (IMF); the distribution of jet opening angles). Follow-up of samples of bursts detected with *Swift* (Gehrels et al. 2004) shows promise in being able to characterise and overcome such biases. The BAT (Burst Alert Telescope) detector is more sensitive to high-redshift bursts than previous missions (e.g. Band 2006), and, due to the rapid localisation of bursts via the onboard XRT (X-Ray Telescope), ground-based follow up of afterglows (yielding information constraining the physical properties of the afterglow, for example redshift, spectral slopes, light curves and jet-break times) is much more systematic.

However, the true proportionality between the global GRB and star formation rates has yet to be definitively established. It is plausible, for instance, that an otherwise direct relation is complicated by dependence on conditions local to the GRB. For example, it is thought that metallicity could play a role in the GRB formation process (e.g. Fynbo et al. 2003; Fruchter et al. 2006). Before one can begin to exploit the new GRB catalogue produced by a mission such as *Swift*, it is of the utmost importance to characterise such effects.

One of the most significant contributors to the star formation rate density at high redshift is the submillimetre galaxy (SMG) population (e.g. Smail, Ivison & Blain 1997; Hughes et al. 1998; Scott et al. 2002; Borys et al. 2003; Mortier et al. 2005). Surveys with submm/mm bolometer arrays such as SCUBA (Submillimetre Common-User Bolometer Array) on the James Clerk Maxwell Telescope (JCMT), and MAMBO (Max Planck Millimetre Bolometer) on the IRAM (Institut de Radioastronomie Millimétrique) 30m telescope, have revealed a population of galaxies forming the bulk of their stars in regions optically thick with dust, such that most of their extremely high luminosity ($L \sim 10^{12-13}\mathrm{L}_{\odot}$) is emitted in the rest-frame far infrared region. Fits to the submm source counts and the FIR background imply that the integrated power reprocessed by dust contributes a major fraction of the total luminous energy emitted throughout cosmic history (Blain et al. 1999).

Taken together, these facts suggest, all other things being equal[1], that highly star-forming SMGs ought to yield a high rate of GRBs; conversely, that a high fraction of GRB host galaxies should turn out to be luminous submillimetre sources. Follow up of GRB hosts in the millimetre and submillimetre bands therefore provides one of the most important calibrators of the role of GRBs as star formation indicators.

For this reason, in recent years, there have been a number of targetted submm studies of GRB hosts, predominantly carried out at 850μm using SCUBA on the JCMT (Berger et al. 2003, Smith et al. 1999, 2001, Barnard et al. 2003). An overview and an analysis is provided by Tanvir et al. (2004). They compared observations made with JCMT/SCUBA with model predictions made assuming a direct proportionality between the GRB rate and the star formation rate. They discovered that, relative to these predictions, observations show a deficit of bright ($\gtrsim$4mJy) sources. Although statistically only marginally significant, this effect could, if confirmed, have important ramifications for derivations of the global star formation history based on GRB surveys. In all, only three GRB hosts (GRB 000210, z=0.85; GRB 000418, z=1.12; GRB 010222, z=1.48) out of 23 with 850μm RMS values <1.4mJy (Tanvir et al. 2004) have been securely detected in the submm. They all lie around the 3mJy level at 850μm, which, though faint, nevertheless implies dust-rich ($M_{\mathrm{d}} \sim 10^{8-9}\mathrm{M}_{\odot}$), massively star-forming (SFR$\sim$100–1000$\mathrm{M}_{\odot}\mathrm{yr}^{-1}$). On the other hand, optical/NIR photometry of these hosts reveals stellar populations that suffer little dust extinction and have low star formation rates ($\sim$1–10$\mathrm{M}_{\odot}\mathrm{yr}^{-1}$) (Gorosabel et al. 2003). This illustrates the importance of submm observations in understanding the properties of GRB hosts: relying on optical data alone, their true significance could easily be overlooked. It is thus important to study wider samples of hosts, and especially to hunt for additional detections, to test whether the existing submm-bright sample is typical or unusual. We are in the process of obtaining X-ray observations of the submm-detected sample which should settle this question.)

The present paper pursues these ideas further. The paper falls into two parts. First, we present new mm and submm observations. The former were obtained using the MAMBO2 bolometer array on the 30m IRAM Pico Veleta telescope, as the preliminary part of the first millimetric survey explicitly targetting GRB hosts[2]. The submm data (850 and 450μm) were obtained using SCUBA on the JCMT. The targets include two of the most extreme GRB hosts known (the reddest and the faintest), deliberately selected as the most promising candidate submm galaxies. Of particular interest, we have obtained deep photometry, at all three wavelengths (450/850/1200μm), of the reddest afterglow/host found to date, GRB 030115.

In the second part of this paper, we develop models to constrain the relation between GRBs and their host galaxies. Using models of the luminosity distribution and evolution of submm galaxies, we derive fits to the luminosity function of GRBs under the assumption that the GRB rate is a function of the star formation rate/far-infrared luminosity of the galaxy. Based upon these fits, we estimate the flux distributions expected at mm and submm wavelengths, which will facilitate comparison between models of the cosmic star formation history, with future mm and submm surveys of the host galaxies of GRBs detected by *Swift*.

2 OBSERVATIONS

2.1 SCUBA/JCMT observations

The question arises, from previous work, as to whether any GRB host galaxies are similar to SMGs For example, the three submm-detected hosts all have bluer colours than typical of submm galaxies. To address this question, we first used JCMT/SCUBA to target a specific host whose properties indicate it to be a promising candidate dust-rich, submm

[1] One way in which they may *not* be equal would be, for example, if a higher than anticipated fraction of SCUBA galaxies were powered by AGN

[2] Note that the host of GRB 010222 was serendipitously detected at 1.2mm during a mm search for its *afterglow*

galaxy. GRB 030115 has the reddest optical colours measured for a GRB host, implying the presence of a large mass of dust, and a (photometric) redshift (z=2.5) placing it near the peak of the redshift distribution measured for submm galaxies (Chapman et al. 2003). In these respects, this object constrasts markedly with the three submm-detected hosts, all of which have $R - K < 3$ and $z < 1.5$.

We obtained new 850μm and 450μm observations of GRB 030115 with JCMT/SCUBA on 2005 January 27 and 28. SCUBA was used in standard photometry mode, with a chop throw of 60 arcsec in azimuth. The zenith opacity was measured via skydips and the JCMT water vapour monitor, and remained within the range $0.065 < \tau_{225\mathrm{GHz}} < 0.08$ on 20050127 and $0.055 < \tau_{225\mathrm{GHz}} < 0.06$ on 20050128. Flux calibration was obtained from the planets Uranus and Mars and several secondary calibrators. Data were reduced both manually using the SURF package, and via the ORAC-DR pipeline. Additional sky removal was achieved by using off-source bolometers to estimate the background.

GRB 030115 had previously been observed by JCMT/SCUBA in Target of Opportunity mode commencing 2003 January 18, 3.3 days after the burst, for a total of two hours: an upper limit of 6mJy (3σ), at 850μm, was reported by Hoge et al. (2003). Since no afterglow was detected, we can use this measurement as an additional upper limit on the submm flux of the host galaxy. We re-reduced the archived data in the same manner as described above, to find fluxes as reported in Table 1.

2.2 IRAM-30m/MAMBO2 1.2mm data

Using the 117-element Max Planck Millimetre Bolometer (MAMBO) detector on the Institut de Radiostronomie Millimétrique (IRAM) 30m Pico Veleta telescope, we obtained observations of five GRB hosts between December 2004 and April 2005, via pooled (service) observing mode. Selection of the targets was designed to improve the redshift distribution of the overall submm/mm GRB host sample, in particular to try to eliminate a possible bias toward low redshift (see Section 3.2.2). All the observed targets lie at $z > 1$, and their mean redshift is 2.1.

Observations were carried out at a wavelength of 1.2mm using MAMBO2 in On–Off mode. Sky opacity was monitored frequently by performing skydips; regular pointing and focus checks were carried out; and flux calibration was obtained from standard sources. The data were reduced using the NIC software package, which forms part of the GILDAS distribution[3]. The principles are similar to the SCUBA data reduction described above, for example the use of off-source bolometers to facilitate sky subtraction. Details of the observations, and final fluxes of the GRB hosts, are reported in Table 2.

2.3 Results

None of the hosts is detected, either at 1.2mm with MAMBO or at 850/450μm with SCUBA. Moreover, the stacked, inverse-variance–weighted mean flux of our sample of five new 1.2mm observations is −0.11±0.27, consistent with a zero flux for this sample. For comparison, the weighted mean 850μm flux of the sample discussed in Tanvir et al. (2004) is 0.93±0.18, which could be interpreted as a true measure of the flux of the "typical" GRB host (though as discussed by Tanvir et al., the weighted mean carries an "observer bias" in that sources with higher fluxes tend to be observed to greater depth to attempt to secure detections. The unweighted mean of their sample is 0.58±0.36mJy). However it is difficult, with such a small sample, to draw any firm conclusions, and we emphasise that investigation of the millimetric properties of GRB hosts is ongoing, the present dataset representing merely a pilot study.

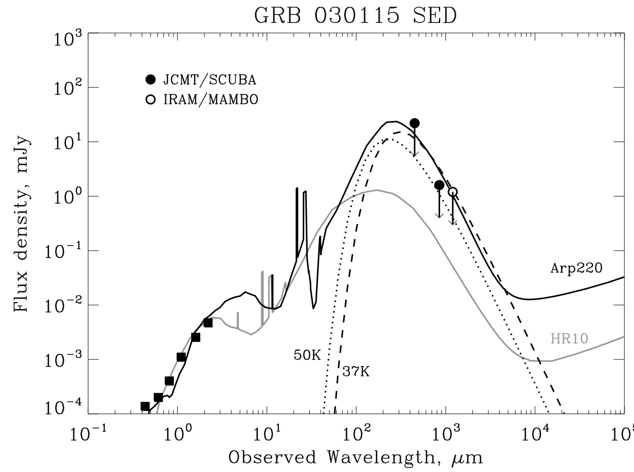

Figure 1. Broad-band SED of the host galaxy of GRB030115, showing optical and near-infrared photometry (squares: Levan et al. 2006) together with SCUBA submm (filled circles) and MAMBO mm (unfilled circle) upper limits (2σ). For comparison, model SEDs of the template galaxies, the prototype ultraluminous infrared galaxy Arp220 and the prototype extremely red object HR10, redshifted to the rest-frame of GRB030115 (assuming the photometric redshift z=2.50 derived by Levan et al. (2006)) has been plotted. The models were produced by the stellar spectral evolution code GRASIL of Silva et al. (1998), normalised to the NIR/optical flux of 030115. Our submm data indicate that GRB 030115 is marginally inconsistent with this Arp220-like SED, although an HR10-like SED cannot be ruled out. Also plotted are two isothermal SEDs normalised so as to have the far infrared luminosities implied by the optical data and the inferred extinction. The dashed line has T=37K, β=1.5, canonical values commonly assumed for submillimetre galaxies, but is ruled out by our submm limits. The dotted line shows that to be consistent with the data, hotter dust is required (in this case T=50K). Observations in the mid-infrared, for example with *Spitzer*, would be required to fully constrain any hot dust component.

Two notable hosts we now discuss individually.

2.3.1 GRB 030115

Coadding all the data obtained for GRB 030115, we find flux densities 0.0±0.8mJy at 850μm, 7±11mJy at 450μm and 0.0±0.8mJy at 1.2mm. We note that this GRB was also observed using MAMBO by Bertoldi et al. (2003), on 20030116 and 20030118 (i.e. shortly after the burst), to attempt to detect the afterglow. Their non-detection (0.4±0.9mJy) can, again, be combined with our new data, to yield a total flux 0.2±0.6mJy. Thus although this host was not detected,

[3] http://www.iram.fr/IRAMFR/GILDAS/

Table 1. Summary of JCMT/SCUBA observations of GRB 030115. Zenith opacities are shown at 225GHz, as a range appropriate to the time of observations.

UT date	Observation time (min)	$\tau_{225\mathrm{GHz}}$	850μm flux (mJy)	450μm flux (mJy)
20050127	40	0.068–0.070	3.2±1.9	71±34
20050128	120	0.055–0.058	−1.0±1.1	−1±12
20030118	115	0.083–0.086	0.0±1.7	9±65

Table 2. Details of our new MAMBO2 1.2mm observations of GRB hosts. Zenith opacities are shown as a range. Quoted fluxes are the final values obtained by coadding all the datasets

GRB	z	UT Date	Observing Time (min)	Opacity (τ)	Final 250GHz flux density (mJy)
GRB 020124	3.20	20050201	60	0.17–0.19	0.28±0.60
		20050224	30	0.17–0.18	
		20050226	30	0.25–0.34	
		20050327	30	0.30–0.35	
GRB 021211	1.01	20050223	30	0.09–0.10	0.07±0.53
		20050224	30	0.18–0.20	
		20050226	30	0.25–0.34	
		20050327	30	0.30–0.35	
GRB 030115	2.5	20050223	25	0.14–0.15	0.01±0.76
		20050224	30	0.17–0.18	
GRB 030226	1.98	20050120	60	0.26–0.28	−0.29±0.66
		20050224	30	0.10–0.12	
GRB 030227	1.6	20041217	95	0.17–0.20	−0.54±0.53
		20050226	30	0.25–0.34	
		20050327	30	0.24–0.30	

we nevertheless possess reasonably strong upper limits at all three wavelengths. (We stress, however, that the 450μm measurement in particular carries a substantial calibration uncertainty. Such a deep short-wave limit is rare, but it must be used with caution.) The 850μm RMS, in particular, would have been easily sufficient to have detected the three submm-bright GRB hosts known to date (e.g. Tanvir et al. 2004).

This object is of particular importance in understanding the host galaxies of GRBs. As noted, it is the reddest GRB host observed to date, with a colour $R-K \approx 5$ (Levan et al. 2006: hereafter L06) that qualifies it as an ERO (Extremely Red Object). The afterglow, too, is exceptionally red ($R-K \approx 6$), providing further evidence for intrinsic extinction. Although no spectroscopic redshift was measured, L06 determine a photometric redshift $z = 2.5 \pm 0.2$. Adopting the calibration determined by Meurer, Heckman & Calzetti (1999) for local starburst galaxies, the extinction implied by the rest-frame ultraviolet slope can be used to estimate the far infrared luminosity from the observed optical flux, assuming that the absorbed UV photons are reradiated in the FIR/submm. The extinction at 1600Å is estimated this way to be 5.3, giving a predicted $L_{\mathrm{FIR}} \approx 2.4 \times 10^{12} \mathrm{L}_{\odot}$. Depending on the adopted stellar (IMF) initial mass function and star formation history, this luminosity implies a formation rate of massive stars in the range $\approx$100–500$\mathrm{M}_{\odot}\mathrm{yr}^{-1}$. Converting the luminosity to a predicted submm flux depends upon the assumed dust temperature, but for a "typical" ULIRG SED (T=40K, β=1.5), the predicted 850μm flux is $\approx$2.5mJy. This is inconsistent with our measurement.

In Figure 1 we plot the optical and near infrared photometry for this galaxy, together with the new mm and submm upper limits. For comparison, we have also plotted (shifted to the rest frame of GRB 030115) SEDs of the canonical ultraluminous infrared galaxy Arp220, and the canonical extremely red galaxy HR10. If this Arp220 template is normalised to the optical/NIR points, it is marginally inconsistent with the submm limits, although this represents an extreme case, and the data cannot rule out an HR10-like SED. The dashed line, meanwhile, shows an isothermal SED (T=37K, β=1.5) having the FIR luminosity predicted from the optical/NIR flux and inferred extinction. Again this is inconsistent with the submm limits, but can be accommodated if the dust temperature is increased (dotted line).

2.3.2 GRB 020124

Another noteworthy member of the sample is GRB 020124. Spectroscopy of its afterglow revealed a high column-density (N_H=$10^{21.7}$) Dampled Lyman Alpha (DLA) system at z=3.2 (Hjorth et al. 2003b). Nonetheless, the host galaxy was not detected in deep optical searches with *HST*, down to $R > 29.5$ (Berger et al. 2002). One explanation for this faintness is that the host galaxy is dust-rich, and therefore plausibly a mm/submm source. Against this interpretation, the small extinction ($A_V < 0.2$) inferred from afterglow reddening implies a low gas–dust (Hjorth et al. 2003b), although it is possible that dust in the vicinity of the GRB is destroyed by its intense, beamed radiation (Waxman & Draine, 2000) hence the line of sight to the afterglow may not be representative of the host galaxy as a whole. Nevertheless, our 1.2mm upper limit constrains the possible dust mass of the host galaxy to $\lesssim 10^8 M_\odot$ (varying inversely with assumed dust temperature), which would tend to disfavour a highly extinguished host galaxy.

3 MODELLING THE GRB HOST GALAXY SUBMM FLUX DISTRIBUTION

In this section we explore the degree to which existing and future submm observations might be able to constrain the efficacy of GRBs as tracers of the star formation rate. Using models of the luminosity and redshift distributions of both SMGs and GRBs, we can predict the submm flux distribution that would be obtained for GRB-selected galaxies.

3.1 Method and assumptions

A preliminary calculation along these lines was first performed by Ramirez-Ruiz, Trentham & Blain (2002). We adopt their assumptions concerning the properties and evolution of SMGs, as described by the models of Blain et al. (1999, 2001). Briefly: the submm luminosity function is based on the local 60μm luminosity function (Saunders et al. 1990), with luminosity evolution described by $\Phi(L, z) = n(z)\phi(L/g(z))$. All submm galaxies are assumed to have an identical isothermal dust SED, whose temperature is a parameter that can be determined by insisting that counts in the mid-infrared are jointly fit. When an emissivity index β=1.5 is assumed, a best fit temperature T=37K results from fits to *ISO* and SCUBA counts (See Blain et al. 1999 and Blain 2001 for full details.)

To model the properties and statistics of GRBs, we first of all assume that the gamma-ray spectrum is described by a Band (1993) function, using values of the spectral indices α=−1, β=−2 and cut-off energy E_0=200keV (rest-frame). We investigate two common parametrizations of the peak luminosity distribution: (1) a log-normal luminosity function (specified by a mean luminosity L_0 and a width σ), and (2) a Schechter (1976) function (specified by a characteristic luminosity L_* and an index γ). In each case, $\rho(z)$, the (comoving) GRB rate density as a function of redshift is derived from the global star formation rate density, $\rho_{\rm GRB}(z) = \eta_{\rm GRB} \times \psi_*(z)$— e.g. as calculated from the submm models. Similarly, the GRB rate per galaxy is assumed to be proportional to the galaxy's far-infrared luminosity. Initially, we assume that $\eta_{\rm GRB}$— the "efficiency" of GRB production— is a constant. However, in general we may consider cases where η is a function of redshift, or of host galaxy properties (see below). The parameters L_0, L_*, σ and γ are then determined, for each star formation history, by fitting the flux distribution of long-duration ($t_{90} > 2$s) GRBs in the BATSE 4B catalogue (Paciesas et al. 1999).

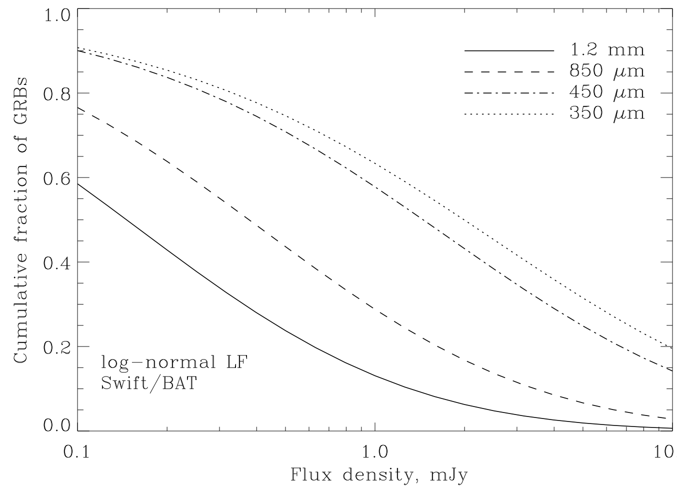

Figure 2. Predicted fraction of GRB hosts brighter than a given flux density, plotted for four different wavelengths in the submm/mm regime. This model displayed here is assumes a log-normal high-energy luminosity distribution for long-duration GRBs (parameters estimated by fitting to the peak flux distribution of the BATSE-4B catalogue), and is calculated for the sensitivity of *Swift*/BAT. However, varying these parameters does not have a dramatic effect upon the results, at least compared with the other uncertainties involved (for example, the SED assumed to describe submm galaxies and GRB hosts).

For this purpose, we adopt a limiting photon flux sensitivity 0.27 ph cm^{-2} s^{-1}, corresponding to the median of the BATSE sensitivity distribution determined by Guetta, Piran & Waxman (2005).

3.2 Results

3.2.1 *Flux distribution*

In Figure 2, we show the predicted cumulative fraction of GRB hosts above a given flux density, for a range of submm/mm wavelengths. In this case, we have assumed a detector sensitivity appropriate for *Swift*/BAT, based upon the intercomparison between BAT and BATSE made by Band (2006). These results correspond to a log-normal GRB luminosity distribution. However, calculations for a Schechter function give very similar results.

In general, the GRB descriptors appear not to affect the *relative* numbers significantly (so long as they represent reasonable fits to the number counts). The adopted submm properties have a larger effect. In particular, we have assumed that GRB host galaxies share a common, isothermal SED— an SED moreover identical to that of submm galaxies. In reality it is possible that the mean dust temperature of GRB hosts is different from the 37K assumed here, and that across the sample a distribution of temperatures is to be found. Testing the effect of this on our predictions is not trivial, since the dust temperature is a parameter of the Blain et al. (1999) submm galaxy evolution models. A detailed refit of the SCUBA counts is beyond the scope of this present work, but for now we can obtain a simple indication of the effect of varying the temperature by taking note of the correlations between the uncertainties in the model parameters of Blain et al. (1999), and rerunning our calculation

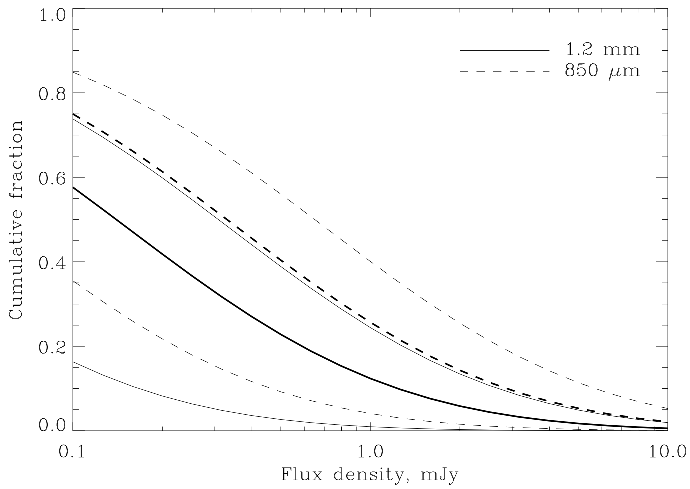

Figure 3. Effect of varying the assumed temperature on two of the wavelengths plotted in Figure 2. The bold lines correspond to the "best fit" temperature as used in Figure 2, while light lines illustrate a plausible range of temperatures (30–50K, top to bottom). Recall that the submm upper limits on the host of GRB 030115 imply a temperature toward the upper part of this range. In reality, both GRB hosts and the submm galaxy population in genernal are likely to exhibit a distribution of temperatures: this calculation assumes one SED for all. A hotter than average temperature for the GRB hosts might explain the paucity of submm detections to date.

using the new parameters. Results for a plausible temperature range are shown in Figure 3. Although the uncertainty is probably somewhat exaggerated (because it assumes all submm galaxies are affected in the same way) the effect is much larger than that due to any uncertainty in the GRB properties. The submm SEDs of GRB hosts are ill-enough constrained that it seems plausible that a hotter than average dust temperature— as our limits for GRB 030115 would imply— could account for the paucity of detections to date.

At 1.2mm, we would expect to have detected ∼10–15 percent of a sample with RMS ∼0.5–0.6mJy, assuming the T=37K model. This could increase to as much as ∼20–25 percent if the temperature were permitted to be as low as 30K, but would become negligible at temperatures as high as 50K. The predicted flux distributions enable us to calculate the average flux density of a large sample, to compare with the coadded (detected plus non-detected) fluxes from observations. The 37K model predicts $< S_{850} >\approx 0.8$mJy, $< S_{1.2} >\approx 0.4$mJy. Recall that Tanvir et al. (2004) find stacked fluxes 0.93±0.18 (weighted mean) and 0.58±0.36 (unweighted), both consistent with this prediction. Our 1.2mm mean, on the other hand, is marginally inconsistent with the prediction. Our sample of five is, however, too small to confirm or reject any of the models, but continued study of homogeneously-selected host samples should improve the constraints. Ultimately, greater sensitivity will be attained by taking advantage of forthcoming facilities such as ALMA (or even existing facilities such as *Spitzer*): then it will be possible to reach limits deep enough to discriminate between models.

3.2.2 Predicted redshift distribution

Figure 4 compares the predicted redshift distribution of all GRBs (thick solid line) with observed, spectroscopically-derived redshifts (light-shaded histogram). Also shown are: the variation of the expected fraction of submm-bright hosts with redshift, $\frac{d}{dz}n(S_{850} > 3mJy)/\frac{d}{dz}n(total)$ (thick dashed line); and the redshift distribution of the submm-observed sample (dark-shaded histogram). Some care must be taken when interpreting the observational data, since the observed distribution is derived from a rather inhomogeneous input sample. Not only does the sample consist of bursts detected by a range of missions, but, insisting upon spectroscopic follow-up inevitably introduces strong biases— for example, toward lower-redshift bursts, toward those that are intrinsically brighter, or toward those suffering less dust extinction from their hosts.

From the figure it is clear that most of the existing submm-observed GRB sample lies at lower redshift than the predicted peak in the submm-bright fraction— and indeed the observed peak of the redshift distribution of submm galaxies (Chapman et al. 2003). This redshift bias is, therefore, another possible explanation of the lack of submm detections in the existing host sample. Now, however, afterglow redshift determination is more systematic, with the accurate localisation provided by the XRT and UVOT instruments on board *Swift*, and rapid ground-based follow-up via a suite of robotic and semi-robotic telescopes. Submm/mm follow-up of samples resulting from such campaigns is likely to place much more secure constraints on the star-forming properties of GRB host galaxies than has been possible hitherto.

3.2.3 Dependence of GRB rate on metallicity

One important factor that might ultimately mitigate against the formation of GRBs in dust-rich galaxies is the role that metallicity is thought to play (e.g. Fruchter et al. 2006). According to the "collapsar" model (MacFadyen & Woosley, 1999), a low metal abundance allows the progenitor to retain a high mass and angular momentum, favouring the production of a black hole and accretion disk. High detection rates of Lyman-α emission from GRB hosts (Fynbo et al. 2003) could be taken as evidence that these systems are indeed metal-poor. If this metallicity dependence is correct, it hold consequences both negative and positive for the use of GRBs as star formation indicators. Whilst, on the one hand, complicating the conversion between GRB and star formation rate, it suggests that GRBs may instead be the ideal means of pinpointing metal-poor galaxies— in particular low-mass, unenriched systems at the highest redshifts which are most likely to be missed in other surveys.

It is therefore important to explore the possible effects of a metallicity dependence. To do so, we place a redshift dependence on the GRB rate density—SFR density conversion factor $\eta_{\rm GRB}(z)$. The evolution of the average metallicity with redshift is given by the submm galaxy models (Blain et al. 1999). This is converted to a relative efficiency of GRB production using an *ad hoc* recipe— which ultimately may be unrealistic, but, in the absence of any compelling observational or theoretical guidelines, it serves amply to illustrate the effects. A sample predicted redshift distribution is plotted in Figure 4 (thin curve). As expected, the peak

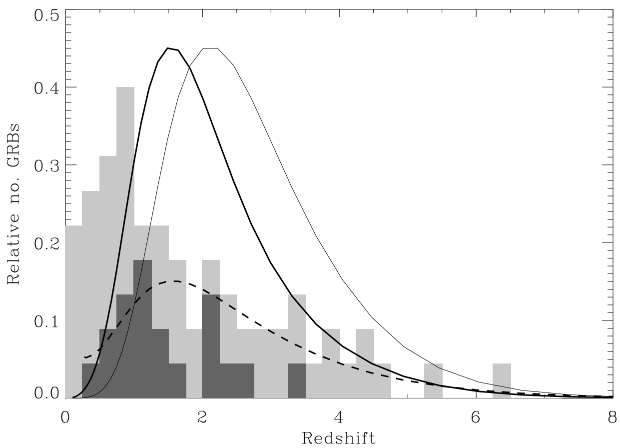

Figure 4. Predicted (curves) and observed (histograms) redshift distribution of GRBs. The thick, continuous curve is the prediction from the basic submm galaxy model, assuming a detector sensitivity appropriate for *Swift*/BAT. The thick dashed line illustrates the variation with redshift of the fraction of submm-bright ($S_{850} > 3$mJy) hosts. The light-shaded histogram shows the distribution of all GRBs with spectroscopically-confirmed redshifts, while the dark-shaded histogram shows the subset of this sample for which sensitive submm photometry has been carried out. Finally, the light continuous curve is a variation on the basic model incorporating a dependence of the GRB formation efficiency on the global average metal abundance. The peak is, as one would expect, shifted to higher redshift, resulting in a distribution more consistent with that emerging from spectroscopic follow-up of *Swift* GRBs. (N.B. the vertical scale is appropriate for the dashed line (submm-bright fraction): the remaining curves and histograms are scaled arbitrarily.)

is shifted toward higher z where the average abundance of heavy elements is smaller. However, without separately encoding galaxy-to-galaxy variations in the metal abundance, the effects on the submm flux distribution are small.

This calculation is, we emphasise, only illustrative at present. For example, it may be more appropriate, for GRB hosts, to consider metallicities traced by optical galaxy surveys, rather than submm surveys as used here. As the redshift distribution of GRBs becomes more fully sampled, (for example via spectroscopic follow-up of large samples of *Swift* bursts), it will soon be possible to place constraints on a wider range of models in this way.

4 SUMMARY

Following from the previous study of Tanvir et al. (2004), we have further investigated the millimetre/submillimetre properties of the host galaxies of GRBs, in order to characterise the efficacy of GRBs as star formation indicators. Specific increments over the T04 study include: (1) we have conducted the first survey of GRB hosts at millimetric wavelengths, with the MAMBO2 bolometer array on the IRAM 30m Pico Veleta telescope. None of these targets was detected, down to an average RMS ≈0.6mJy at 1.2mm; (2) we obtained deep submm photometry of GRB030115, whose high intrinsic extinction inferred from its optical/NIR spectral slope make it a promising candidate submm galaxy. Despite its ERO-like optical colours, however, this galaxy is not detected in the mm/submm, to deep limits at 850μm (σ=0.8mJy) and 450μm (σ=11mJy); (3) we have modelled the redshift and flux distribution of GRB hosts, assuming a link between GRBs and the submm galaxy population. A novelty of these models is that they take account of the metallicity bias widely proposed to affect the GRB-to-star formation rate conversion. As such they potentially have much wider applicability than the derivation of submm properties, and we will further develop these ideas in future publications (Priddey et al., in prep.).

The non-detection of GRB 030115 is revealing. One might contrast this result with the three GRBs that *do* possess submm detections, for their optical/NIR colours are much bluer. The broadband spectrum of the GRB 030115 host is inconsistent with the SED of an extremely luminous infrared galaxy such as Arp220 or with a cool, isothermal model, but hotter dust ($\gtrsim$50K), or template SEDs of other submm-luminous galaxies, cannot be ruled out. Observation in the mid-infrared with missions such as *Spitzer* should also be able to constrain any hot dust component too faint to be seen in the submm.

We emphasise that this work is ongoing: in the imminent future we will be able to draw upon larger, post-*Swift* samples of GRBs to ensure a uniform sample selection—enabling, for example, a more uniform redshift distribution. For the moment, it seems that the trend of a low submm detection rate of GRB hosts, seen in previous surveys, is maintained.

What are the implications of a low mm/submm detection of GRB hosts? We have shown that there is sufficient uncertainty in models and underlying assumptions, as yet poorly constrained by observation (for example the adopted dust temperature) that a correlation between massive, dust-enshrouded star formation and GRB production cannot be firmly ruled out. Sample selection biases (e.g. against high redshift and highly extinguished bursts) are also likely to have played a significant role in previous studies. Our models indicate that redshift bias in particular could account for the lack of detections within existing surveys. The new observations reported here (5 hosts all at $z > 1$, one highly extinguished host and one extremely faint host) were taken in part to alleviate such problems. Prior to ALMA, observations of consistently followed-up samples with existing facilities (e.g. IRAM-30m, APEX) must be made to enable us to make further progress in exploring these effects. The capabilities of *Swift*, combined with efficient ground-based follow up, show promise in being able to yield such a sample.

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