Mon. Not. R. Astron. Soc. **398,** 1615–1620 (2009) doi:10.1111/j.1365-2966.2009.14710.x

Submillimetre detection of the $z = 2.83$ Lyman-break galaxy, Westphal–MM8, and implications for SCUBA2

S. C. Chapman[1,2]★† and C. M. Casey[1]

[1] *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*
[2] *Department of Physics and Astronomy, University of Victoria, Victoria, BC, V8P 1A1, Canada*

Accepted 2009 February 27. Received 2009 January 27; in original form 2008 June 26

ABSTRACT

We present confusion-limited submillimetre (submm) observations with the Submillimetre Common-User Bolometer Array (SCUBA) camera on the James Clerk Maxwell Telescope of the $z = 2.83$ Lyman-break galaxy (LBG), Westphal–MM8, reaching an 850 μm sensitivity even greater than that achieved in the SCUBA map of the *Hubble Deep Field* region. The detection of MM8 ($S_{850\,\mu\mathrm{m}} = 1.98 \pm 0.48$ mJy), along with the literature submm detections of lensed LBGs, suggests that the LBG population may contribute significantly to the source counts of submm-selected galaxies in the 1–2 mJy regime. Additionally, submm-luminous LBGs are a viable progenitor population for the recently discovered *evolved* galaxies at $z \sim$ 2–2.5. These observations represent an important baseline for SCUBA2 observations which will regularly map large regions of the sky to this depth.

Key words: galaxies: active – galaxies: formation – galaxies: individual: Westphal–MM8 – infrared: galaxies.

1 INTRODUCTION

Lyman-break galaxies (LBGs) represent the largest population of high-redshift ($z > 3$) star-forming galaxies yet discovered (Steidel et al. 1999), likely comprising a significant percentage of the far-infrared (FIR) background (Adelberger & Steidel 2000). The dust-corrected star formation rate (SFR) distribution of LBGs, n(SFR), shows significant numbers of $z \sim 3$ galaxies with SFR $\gtrsim 100\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$ (representing $S_{850\,\mu\mathrm{m}} \sim 1$ mJy depending on the adopted dust parameters). However, the search for submm counterparts to LBGs has proved difficult due to uncertainties in the relations used to predict the rest-frame FIR luminosity from the ultraviolet (UV), and also photometric errors. Since dusty, submm-luminous LBGs would characteristically have their UV continuum highly suppressed due to dust extinction, it is difficult to distinguish between a truly prodigious star former and a less luminous galaxy with an intrinsically low SFR and large photometric errors. The FIR and submm emission from LBGs, their dust content and their contribution to the FIR background light remains an unsolved puzzle for which major progress can only be expected with the new sensitive instruments and telescopes, such as Submillimetre Common-User Bolometer Array 2 (SCUBA2) and ALMA.

A few highly lensed LBGs have been detected in the submm wavelengths, and represent good test cases for the FIR properties of $z = 3$ star-forming galaxies (e.g. Smail et al. 2007). However, these objects could suffer from differential lensing of the UV and FIR components (e.g. Borys et al. 2004) and may be more difficult to gauge relative to the general population. The sole submm detection of an unlensed LBG thus far has been for the extremely red ($R - K \sim 5$) specimen, Westphal–MMD11 (Chapman et al. 2000). Baker et al. (2004) demonstrated through sensitive CO molecular gas observations that it is not a typical member of the submm galaxy population (cf. Greve et al. 2005). While one possibility is that the dust in LBGs is significantly hotter than typical submm galaxies (making them harder to detect at 850 μm), similar to the radio-selected $z \sim 2$ ultraluminous infrared galaxies in Chapman et al. (2004a) and Casey et al. (2009), it would be surprising if this characterized the bulk of the LBG population since nothing about their properties suggests that they would have hotter dust on average than other classes of star-forming galaxies. Several LBGs have been detected at 24 μm using *Spitzer* (Huang et al. 2005; Reddy et al. 2006)), although it is not yet clear whether this excess 24 μm emission comes from a truly high SFR, intricacies in the aromatic dust features or a power-law AGN component. Deep submm observations comparable to those presented in this work will be the ultimate diagnostic for star formation in high-z LBGs.

Identified as a LBG in the surveys of Steidel et al. (2003), Westphal–MM8 has from its rest-frame UV spectrum an exceptionally large SFR ($>100\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$, after correction for dust extinction). However, the infrared (IR) colours and overall properties do not single out this object as unusual for the population in any other respect. In this paper, we present deep confusion-limited submm observations of MM8, probing the emission from the dusty component. Throughout we assume a cosmology with $h = 0.7$, $\Omega_\Lambda = 0.72$, $\Omega_\mathrm{M} = 0.28$ (e.g. Hinshaw et al. 2007).

★E-mail: schapman@ast.cam.ac.uk
†Canadian Space Agency, Space Science Fellow.

2 OBSERVATIONS AND ANALYSIS

Westphal–MM8 was observed with the SCUBA (Holland et al. 1999) on the James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawaii. The observations presented here are the combination of the original observation presented in Chapman et al. (2000) (5.4 ks on source) and two archival observations (6.7 and 6.0 ks on source, respectively). The combined observation represents two complete 8-h JCMT shifts centred on this single LBG, and reaches a sensitivity level even deeper than the Hughes et al. (1998) SCUBA map of the *Hubble Deep Field*.

All observations were taken in the standard PHOTOMETRY mode of SCUBA, divided into ~30 min scans with azimuthal chop angle to minimize atmospheric gradients, a chop frequency of 7.8125 Hz and a throw of either 40 or 45 arcsec. All observations were taken between 1998 and 2000 under superb submm observing conditions. The sky rotation over the fixed Nasmyth array coordinate resulted in all angles on the sky being covered by the chop throw (Fig. 1). We make no attempt to fold in the few observations when the source actually crossed another bolometer in an off beam.

Pointing was checked hourly on blazars, and sky-dips were performed routinely to measure the atmospheric opacity directly. The rms pointing errors were below 2 arcsec, while the average atmospheric zenith opacities at 450 and 850 μm were 1.7 and 0.20, respectively. The data were reduced using the STARLINK package SURF (Scuba User Reduction Facility; Jenness & Lightfoot 1998). Spikes were first carefully rejected from the data, followed by correction for atmospheric opacity and sky subtraction using the median of all the array pixels, except for obviously bad pixels and the source pixels. The data were then calibrated against standard planetary and compact H II region sources, observed during the same nights.

All the scans on source were combined with inverse variance weighting. The final signal measured is 1.98 ± 0.48 mJy at 850 μm, with no significant detection at 450 μm. Dividing the data set in half shows a similar detection significance in each half, increasing our confidence that a true detection has been achieved (that the final result is not the bias of any small part of the data set). The MM8 observation is adjacent to three other shorter exposures of LBGs, including the detected MMD11 described above and two others showing insignificant but positive flux density. We combine all these observations into a single map for illustration and comparison (Fig. 1).

At such faint SCUBA flux levels, we must be cautious of both confusion noise and interloping source effects on our signal. The probability that a random galaxy lies within the beam is given by $P = 1 - \exp(-\pi n \theta^2)$, where $n(>S)$ is the cumulative surface density for the population in question and θ is the beam radius. For a flux density of 1.9 mJy, the source counts are about 5000deg^{-2} (e.g. Blain et al. 1999), and so $P \simeq 4$ per cent per pointing. Although nine high-SFR LBG candidates were observed in the original Chapman et al. (2000) sample, the average sensitivity reached was only 1.2 mJy rms. Thus although the chance that at least one of these observations is contaminated by a 1.9 mJy source is then ~27 per cent, the MM8 observation is the only one for which any significant flux would have been measured. In addition, as we shall demonstrate below, the potential *interloper* is highly likely to be drawn from the high-SFR LBG population in the first place, making it even more unlikely that some optically faint source is in fact contributing this submm flux.

The issue of confusion noise (Scheuer 1957; Condon 1974) considers the fluctuations due to undetected sources which contribute to our error bars. A full discussion of the effects of confusion on deep SCUBA photometry observations can be found in Chapman et al. (2000). Blain, Ivison & Smail (1998) quote a value of 0.44 mJy for the variance due to confusion, derived from their source counts. This is comparable to our measured rms for MM8, and since the errors add in quadrature, this is the dominant source of noise. The actual flux of MM8 may therefore be skewed slightly brighter than our measured value. Again, however, we note that the contribution to the confusion noise from the 1–2 mJy submm sources is likely to arise from the LBG population itself, and thus by pointing at a known high-SFR LBG, we have somewhat reduced the likelihood of confusion bias. For the other literature, unlensed LBG sources considered in this paper, confusion noise is subdominant and does not significantly affect our result.

We also searched for additional submm sources significantly detected in the deep maps. We detect one additional submillimetre galaxy (SMG) in the outer region of the 850 μm map

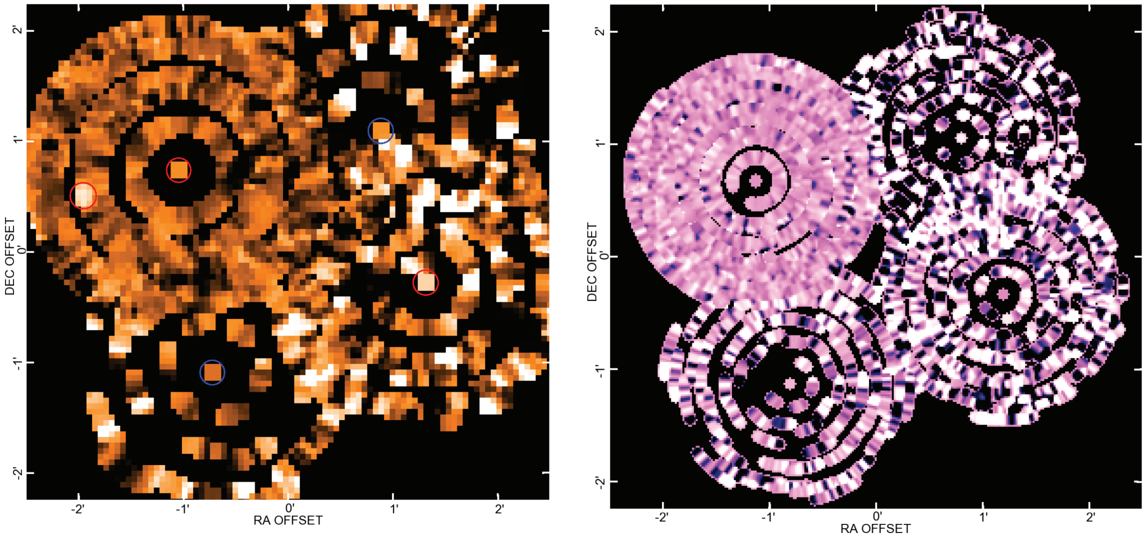

Figure 1. SCUBA 850 and 450 μm images of the region surrounding the LBGs MM8, MMD11. The field is 4.5 × 4.5 arcmin^2, where the 450 μm array covers a slightly smaller area than the 850 μm, but with 191 (versus 37) bolometers. The two detected LBGs, MM8 and MMD11 are circled in red, as is a serendipitously detected SMG in the deep map surrounding MM8.

($S_{850\,\mu\mathrm{m}} = 5.8 \pm 1.4$ mJy), which is marginally detected at 450 μm. While the outer regions of the map are not as deep as the central point, at $\sigma = 1.4$ mJy, it remains one of the deepest maps ever taken by SCUBA, and it is statistically expected that we would detect one source brighter than 5 mJy (e.g. Coppin et al. 2006). None of the LBGs or the new SMG presented in this region is detected in the radio (Ivison et al. 2007) or X-ray (Nandra et al. 2007), and there is no *Spitzer* data covering this area.

3 RESULTS

3.1 MM8 luminosity and dust content

Fig. 2 presents the extant data of MM8 (optical data points from Shapley et al. 2001), including the new SCUBA data discussed in Section 2. Also plotted is the spectral energy distribution (SED) of a possible local analogue to MM8, the star-forming galaxy M82. Although still a relatively extreme object, MM8 represents the faintest galaxy ever detected with SCUBA, comparable to the faintest object in the *Hubble Deep Field* SCUBA observation of Hughes et al. (1998), HDF850.5 ($S_{850\,\mu\mathrm{m}} = 2.1 \pm 0.5$ mJy) or the ultra-deep Abell2218 SCUBA map of Knudsen et al. (2006), SMM J163602.6+661255 with $S_{850\,\mu\mathrm{m}} = 2.8 \pm 0.6$ mJy. This fact emphasizes the difficulty in detecting more typical star-forming galaxies at high redshift in the submm wavelengths with present facilities and achievable sensitivities.

Simply scaling the observed submm photometry from that of Arp220 implies that MM8 has an IR luminosity of $L_{\mathrm{IR}} \sim 2 \times 10^{12}\, h_{70}^{-2}\, \mathrm{L}_{\odot}$, placing it in the ultraluminous class of IR galaxies (Sanders & Mirabel 1996). MM8 displays no evidence of gravitational lensing, appearing point-like in the optical at a PSF scale ~0.7 arcsec. Again, scaling from the Arp220 model, the resulting dust mass in MM8 is $\sim 3 \times 10^{6}\, \mathrm{M}_{\odot}$. Without more data over the SED of MM8, this value possesses a significant uncertainty, but does indicate that MM8 harbours a large quantity of dusty material.

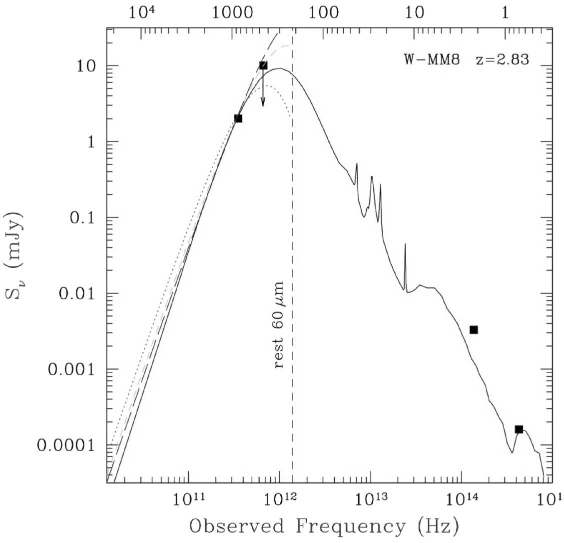

Figure 2. The SEDs of MM8 ($z = 2.83$) as compared to a representative local star-forming galaxy, M82 (solid line). The top axis shows the observed frame wavelength in microns. Also plotted in dashed lines are modified blackbody spectra for emissivity $\beta = 1.5$ and $T_{\mathrm{d}} = 30$, 50 and 70 K (dashed lines), normalized to the 850 μm point. For nearby galaxies, the IRAS 60 μm band has typically been used to estimate SFRs. We have marked the location of this band (in the rest frame) with a vertical dotted line for both objects, as an indication of the extrapolation used in this study relative to nearby objects. Optical *R*- and *K*-band photometry comes from Shapley et al. (2001).

In Table 1, we present measured and predicted 850 μm flux densities along with the UV-derived SFR for the submm-detected LBGs, MM8 and MMD11, and the lensed LBGs with submm or CO detections are available. Of the lensed LBGs, it is noteworthy that SMMJ16359 and MS0451-a were discovered on their submm properties and not through the LBG selection criterion. For the two cases where S_{850} was estimated from the CO luminosity, an additional uncertainty of the order of 50 per cent is likely, as measured directly for the SCUBA-bright population in Greve et al. (2005).

The UV-predicted S_{850} is highly dependent on the dust parameters adopted. We have used the empirical dust curve for M82 which appears to accurately predict S_{850} for MM8, whereas a combination of different dust emissivity (β) and dust temperature would result in significant changes to the predicted submm emission. The uncertainty in this estimate based on the estimated local and high-z dust temperature distributions (e.g. Blain et al. 2004) is ~0.3 dex.

3.2 Implications for the faint submm sources

A correlation is expected between the rest-frame UV continuum and the FIR emission for star-forming galaxies, since much of the UV radiation emitted by hot O- and B-type stars is absorbed by dust and re-radiated at FIR wavelengths in the form of a modified blackbody. Meurer, Heckman & Calzetti (1999) have shown this to be the case for local star-forming galaxies with bolometric luminosities $L \sim 10^{11}\, \mathrm{L}_{\odot}$, with a factor of 2 scatter in the relation.

However, such a relation can only be expected to hold if the bulk of the detected UV and FIR radiation is emitted from the same location in the galaxy. Related is the problem of vastly different optical depth effects in the two wavelength regimes. These issues are verifiable in local galaxies but difficult in high-redshift objects, where typically only the integrated emission is known. For extremely luminous local starburst galaxies, such as Arp220 ($L \sim 10^{13}\, \mathrm{L}_{\odot}$), the dominant UV and FIR components are observed in different spatial locations, and the integrated UV-to-FIR ratio lies significantly above the Meurer et al. (1999) correlation (see Goldader et al. 2002). The UV/FIR relation must be taken as unreliable for such hyperluminous IR galaxies. However, objects like MM8 lie in the interim luminosity regime ($L \sim 10^{12}\, \mathrm{L}_{\odot}$), for which Reddy et al. (2006) have suggested that the UV/FIR relation appears to hold on average based on mid-IR, radio and X-ray stacking observations.

In Fig. 3, we present the measured (or intrinsic) S_{850} versus UV-predicted S_{850} for the LBG sample, depicting the $x = y$ relationship. The two detected LBGs (Westphal–MMD11 and MM8) are highlighted against Bayesian 95 per cent confidence upper limits for the literature sources. We also show the explicit measurement limits for these LBGs as $S_{850} + 1\sigma \times$ rms (mJy). Two fits are made to unlensed LBGs, one using the Bayesian limits and one using the $S_{850} + 1\sigma$ points. The fits are constrained to pass through the origin. In both cases, we exclude MMD11 since its submm luminosity places it in the class of hyperluminous objects (Sanders & Mirabel 1996), and as such its UV/FIR relation is particularly suspect. The five lensed LBGs with submm measurements are reasonably described by the fit to the $S_{850} + 1\sigma$ data, suggesting that the Bayesian limits are likely a conservative estimate of the relation. The relation ($S_{850,\mathrm{measured}} = 0.8 \times S_{850,\mathrm{predicted}}$) is therefore proposed as a high-redshift UV/FIR fiducial for estimation of the LBG contributions to the submm source count.

Table 1. Predicted and measured (intrinsic) submm flux densities for high-SFR Lyman-break galaxies. We give the galaxy designation, RA/Dec., redshift, observed 850 μm flux density, R-band magnitude, the SFR derived from the UV-corrected flux and the 850 μm flux density predicted from the UV data.

Galaxy	RA (J2000)	Dec. (J2000)	z	S_{850}[a] (mJy)	R_{AB} (mag)	SFR $_{\rm UV-corr}$[b] ($\rm M_{\odot}\,yr^{-1}$)	$S_{850-\rm UV}$[c] (mJy)
Unlensed LBGs observed in the SCUBA map							
West–MM8[e]	14:18:23.90	+52:23:07.7	2.829	1.98 ± 0.48	24.13	175 ± 164	1.5 ± 1.1
West–MMD11	14:18:09.71	+52:22:08.5	2.979	5.51 ± 1.38	24.05	173 ± 95	1.2 ± 0.6
Serendipitous SMG discovered in the SCUBA map							
West–SMG1	14:18:29.57	+52:22:54.4	–	5.83 ± 1.39	–	–	–
Lensed LBGs from the literature[d]							
CosmicEye	21:35:12.73	−01:01:42.9	3.074	0.75	20.3	100	2.0
MS0451-a	04:54:10.90	−03:01:07.0	2.911	0.40	22.9	10	0.2
cB58	15:14:22.27	+36:36:25.2	2.723	0.39	20.3	24	0.6
SMM J16359	16:35:54.50	+66:12:31.0	2.517	0.65	23.0	9	0.3
Cosmic Horseshoe	11:48:33.15	+19:30:03.5	2.379	2.03	19.0	80	2.3

[a] S_{850} either measured directly or inferred from CO detections (the latter described in[d]).

[b] Calzetti (1997) attenuation curve corrected, taking into account Monte Carlo simulations of the photometric errors. Simple rms errors are quoted, while in fact the distributions are skewed (Adelberger & Steidel 2000).

[c] Predicted from the UV colours (see Chapman et al. 2000 and Adelberger & Steidel 2000 for detailed discussion).

[d] Properties derived for lensed sources referenced as follows: Cosmic Eye (Coppin et al. 2007), MS0451-a (Chapman et al. 2002; Borys et al. 2004), cB58 (Baker et al. 2004a), SMM J16359 (Kneib et al. 2005 – where we have quoted their central pointing between the multiply imaged galaxy), Cosmic Horseshoe (Laird et al. 2006; Belokurov et al. 2007). In two cases where 850 μm measurements were not obtained (Cosmic Eye and Cosmic Horseshoe) the 850 μm flux was inferred from the CO gas through the relation in Greve et al. (2005), where an additional uncertainty of ∼50 per cent is introduced by the scatter in SCUBA-bright galaxy properties.

[e] The redshift of MM8 appears in Shapley et al. (2001) as 2.829 (as quoted here), while $z = 2.839$ (in a table) and 2.841 (in a figure) are given in Steidel et al. (2003).

4 DISCUSSION

Most of the 850 μm background appears to be produced by objects with $S_{850} \sim 1$ mJy (e.g. Smail et al. 1999), and the data in this paper are consistent with the idea that these dusty 1 mJy sources which dominate the background have UV properties similar to LBGs. With our derived UV/FIR relation at high redshift, we calculate a 1–2 mJy surface density of 3600 $\rm deg^{-2}$ for LBGs with expected SFR $> 100\,\rm M_{\odot}\,yr^{-1}$ over the redshift range $z = 1.5$–3.5 (using the Reddy et al. 2008 luminosity function). This represents >70 per cent of the measured 1–2 mJy submm source counts (cf. Blain et al. 1999; Knudsen et al. 2006), and as such suggests that optical surveys typically uncover the sources which begin to dominate the fainter submm source counts. If all UV-selected $z \sim 3$ with SFRs $\sim 100\,\rm M_{\odot}\,yr^{-1}$ galaxies are as dusty as the present analysis suggests, then UV-selected populations probably produce the bulk of the 850 μm background (see also Adelberger & Steidel 2000).

However, the specific galaxies which dominate the $S_{850} \sim 1$ mJy counts are still a debated issue, where other investigations propose significant contributions from various classes of galaxies selected at different redshift intervals (e.g. Wehner, Barger & Kneib 2002; Webb et al. 2003; Knudsen et al. 2005; Wang, Cowie & Barger 2006). We note first that many high-redshift galaxies selected at longer wavelengths do have colours consistent with the LBG selection (e.g. Reddy et al. 2008), including a substantial fraction of the hyperluminous SMGs (Chapman et al. 2005), and thus one should expect an overlap between the different galaxy classes that are estimated to contribute significantly. The second obvious problem with these analyses is the large (∼15 arcsec) confusion-limited beam sizes of submm/mm measurements, allowing the galaxies of different types which may well cluster together to be collectively measured in the same 850 μm beam. Of note is the low average 850 μm flux for LBGs inferred by Chapman et al. (2000), Peacock et al. (2000) and Webb et al. (2003), <1 mJy. Individual objects in these samples likely have SFRs substantially lower than the UV-inferred SFR due to the photometric uncertainties described in the introduction. Finally, we note the indirect estimates of the SFR. Without direct constraint of the FIR peak for high-redshift, luminous galaxies, there remains substantial uncertainty in estimating how any particular population contributes to the FIR backgrounds.

The discovery, confirmation and full characterization of $z \sim 2$–2.5 evolved galaxies with no ongoing star formation (e.g. Kriek et al. 2008; van Dokkum et al. 2008) demand a sizable progenitor population to rapidly form the stars at $z > 3$. The submm-luminous galaxy population ($S_{850\,\mu\rm m} > 5$ mJy) for the most part cannot fulfil this role as they lie predominantly *at* $z \sim 2$ (e.g. Chapman et al. 2005; Ivison et al. 2007; Clements et al. 2008), coeval with this old evolved population. These submm-selected galaxies have a rapidly declining luminosity function beyond $z > 2.5$, dropping in volume density over 2× from $z = 2$–3, and likely a factor of ∼10 from $z = 2$–4 (Chapman et al. 2005; Pope et al. 2006). However, galaxies with $S_{850\,\mu\rm m} \sim$1–2 mJy could remain to be numerous at $z > 3$ (e.g. Adelberger & Steidel 2000) and would still represent an ultraluminous population.

While we do not extrapolate submm properties explicitly from this single submm detection of a *typical* LBG at $z \sim 3$, we state for reference the expected volume density of $z \sim 3$ LBGs with likely $S_{850\,\mu\rm m} > 1$ mJy (total IR luminosities $L_{\rm IR} > 10^{12}\,\rm L_{\odot}$) from Reddy et al. (2008): $\Phi \sim 3 \times 10^{-4}\,h^{3}_{0.7}\,\rm Mpc^{-3}$, which is very similar to their estimate for $z \sim 2$ indicating little redshift evolution. Contrast bright submm-selected galaxies which would only have $\Phi < 10^{-6}\,h^{3}_{0.7}\,\rm Mpc^{-3}$ at $z \gtrsim 3$ (Chapman et al. 2005).

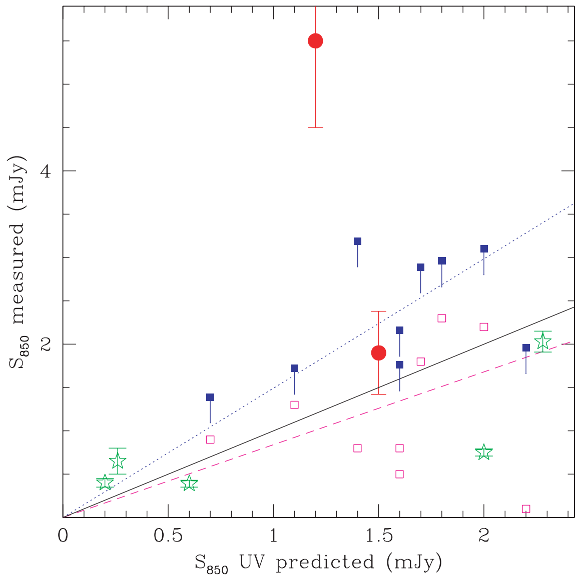

Figure 3. The measured S_{850} versus UV-predicted S_{850} for $z \sim 3$ LBGs, a solid line depicting the direct $x = y$ relationship. The two detected LBGs (MMD11 and MM8) are shown with large red circles. The solid blue squares represent Bayesian 95 per cent upper limits to the LBGs presented in Chapman et al. (2000), while the open squares (magenta) show the measured $S_{850} + 1\sigma$ (mJy) points, where $+1\sigma$ is the minimum offset to bring all values positive. The blue (dotted) line represents a fit to the Bayesian 95 per cent upper limits constrained to pass through the point (0,0), including the detection of MM8, but excluding the extreme object Westphal–MMD11. The magenta line (dashed) is a fit to the $S_{850} + 1\sigma$ points, again excluding Westphal–MMD11. We take this relation as our high-redshift UV/FIR fiducial for estimation of the LBG contributions to the submm source count and FIR background. Five lensed LBGs with submm measurements are also shown as stars. These LBGs reasonably agree with a one-to-one correspondence of predicted/measured 850 μm flux.

Measuring the submm fluxes of large samples of known $z = 2$–4 galaxies will be a cornerstone goal of SCUBA2 (Holland et al. 2003), where vast confusion-limited surveys at both 850 and 450 μm will be achieved. This will allow the extension of this study to large samples of galaxies, although the issue of confusion noise will persist at 850 μm. As shown in Fig. 2, the limit we achieved for MM8 at 450 μm for MM8 is not quite deep enough to discriminate between different dust temperatures (or SED shapes in general). However, the confusion-limited 450 μm sensitivities ($\sim$0.5 mJy rms) listed in the goals of the deep SCUBA2 Legacy programmes[1] are more than sufficient to completely characterize dust temperature distributions even for $z > 3$ galaxies, and the reasons for the submm detectability raised in Section 1 will become clear. E-MERLIN[2] and E-VLA[3] will also be able to detect these populations directly at 1.4 GHz, and in addition constrain their radio sizes, potentially well in advance of being able to study their sizes directly in the submm with ALMA.[4]

Finally, followup of unlensed LBGs (using the Institut de Radioastronomie Millimétrique, Plateau de Bure Interferometer) in molecular CO gas has met with four failures and no successes (Baker et al. 2004b; Tacconi et al. 2008). MM8 represents an obvious candidate for CO followup, however based on the current lack of success, it is likely that ALMA will be required for full characterization of these galaxies dominating the submm background.

5 CONCLUSIONS

We have presented submm observations of the $z = 2.83$ LBG MM8, nominally the deepest SCUBA observation ever taken of a distant galaxy. These observations confirm that this LBG has a large SFR ($\sim$200 M$_{\odot}$ yr^{-1}) as indicated by the dust-corrected UV. MM8 is associated with a large quantity of dust, with an inferred IR luminosity of $\sim 2 \times 10^{12}\, h_{70}^{-2}\, \mathrm{L}_{\odot}$.

Despite the large dust mass, enough of the UV remains in view to provide a clear indication of the expected submm flux. This contrasts with typical submm-luminous galaxies where high-resolution radio and mm-interferometry (Chapman et al. 2004b; Tacconi et al. 2006, 2008) have demonstrated that the bolometrically luminous region can lie significantly offset (several kpc) from UV-luminous regions. This suggests that for less luminous $z \sim 3$ galaxies like MM8, the dust distribution may not hinder the UV/FIR relation to the same extent.

The observations presented here also suggest that individual LBGs from the sample of Chapman et al. (2000) could be similar in submm properties to MM8 ($\sim$1–2 mJy), and SCUBA2 surveys may regularly detect these galaxies in its confusion-limited wide field surveys.

ACKNOWLEDGMENTS

We thank an anonymous referee for helpful comments which improved the manuscript. SCC acknowledges support from the Canadian Space Agency and NSERC. CMC thanks the Gates-Cambridge Trust for support. The JCMT is operated by The Joint Astronomy Centre on behalf of the Particle Physics and Astronomy Research Council of the United Kingdom, the Netherlands Organization for Scientific Research and the National Research Council of Canada. We acknowledge the use of the Canadian Astronomy Data Centre, which is operated by the Herzberg Institute of Astrophysics, National Research Council of Canada.

REFERENCES

Adelberger K., Steidel C., 2000, ApJ, 544, 218
Baker A. J., Tacconi L. J., Genzel R., Lehnert M. D., Lutz D., 2004a, ApJ, 604, 125
Baker A. J., Tacconi L. J., Genzel R., Lutz D., Lehnert M. D., 2004b, ApJ, 613, L113
Belokurov V. et al., 2007, ApJ, 671, 9L
Blain A. W., Ivison R. J., Smail I., 1998, MNRAS, 296, 29L
Blain A. W., Kneib J.-P., Ivison R. J., Smail I., 1999, ApJ, 512, L87
Blain A., Chapman S. C., Smail I., Ivison R., 2004, ApJ, 611, L52
Borys C., Scott D., Chapman S., Halpern M., Nandra K., Pope A., 2004, MNRAS, 352, 759
Calzetti D., 1997, AJ, 113, 162
Casey C. et al. 2009, MNRAS, in press (arXiv:0906.5346)
Chapman S. et al., 2000, MNRAS, 319, 318
Chapman S., Scott D., Borys C., Fahlman G. G., 2002, MNRAS, 330, 92
Chapman S. C., Smail I., Blain A., Ivison R., 2004a, ApJ, 614, 671
Chapman S. C., Smail I., Windhorst R., Muxlow T., Ivison R., 2004b, ApJ, 611, 732
Chapman S., Blain A., Smail I., Ivison R., 2005, ApJ, 622, 772
Clements D. et al., 2008, MNRAS, 387, 247
Condon J. J., 1974, ApJ, 188, 279
Coppin K. et al., 2006, MNRAS, 372, 1621
Coppin K. et al., 2007, ApJ, 665, 936

---

[1] http://www.jach.hawaii.edu/JCMT/surveys/Cosmology.html
[2] http://www.merlin.ac.uk/e-merlin
[3] http://www.aoc.nrao.edu/evla
[4] http://almaobservatory.org

Goldader J. D., Meurer G., Heckman T. M., Seibert M., Sanders D. B., Calzetti D., Steidel C. C., 2002, ApJ, 568, 651
Greve T. et al., 2005, MNRAS, 359, 1165
Hinshaw G. et al., 2007, ApJS, 170, 288
Holland W. S. et al., 1999, MNRAS, 303, 659
Holland W. S. et al., 2003, Proc. SPIE, 4855, 1
Huang J.-S. et al., 2005, ApJ, 634, 137
Hughes D. H. et al., 1998, Nat, 394, 241
Ivison R. et al., 2007, MNRAS, 380, 199
Jenness T., Lightfoot J. F., 1998, in Albrecht R., Hook R. N., Bushouse H. A., eds, ASP Conf. Ser. Vol. 145, Astronomical Data Analysis Software and Systems VII. Astron. Soc. Pac., San Francisco, p. 216
Kneib J.-P., Neri R., Smail I., Blain A., Sheth K., van der Werf P., Knudsen K. K., 2005, A&A, 434, 819
Knudsen K. K. et al., 2005, ApJ, 632, L9
Knudsen K. K. et al., 2006, MNRAS, 368, 487
Kriek M., van der Wel A., van Dokkum P. G., Franx M., Illingworth G. D., 2008, ApJ, 682, 896
Laird E. S., Nandra K., Hobbs A., Steidel C. C., 2006, MNRAS, 373, 217
Meurer G. R., Heckman T. M., Calzetti D., 1999, ApJ, 521, 64
Nandra K. et al., 2007, ApJ, 660, L11
Peacock J. A. et al., 2000, MNRAS, 318, 535
Pope A. et al., 2006, MNRAS, 370, 1185
Reddy N. A., Steidel C. C., Fadda D., Yan L., Pettini M., Shapley A. E., Erb D. K., Adelberger K. L., 2006, ApJ, 653, 1004
Reddy N. A., Steidel C. C., Pettini M., Adelberger K. L., Shapley A. E., Erb D. K., Dickinson M., 2008, ApJS, 175, 48
Sanders D. B., Mirabel I. F., 1996, ARA&A, 34, 749
Scheuer P. A. G., 1957, Proc. Camb. Phil. Soc., 53, 764
Shapley A. E., Steidel C. C., Adelberger K. L., Dickinson M., Giavalisco M., Pettini M., 2001, ApJ, 562, 95
Smail I., Ivison R. J., Kneib J.-P., Cowie L. L., Blain A. W., Barger A. J., Owen F. N., Morrison G., 1999, MNRAS, 308, 1061
Smail I. et al., 2007, ApJ, 654, L33
Steidel C., Adelberger K., Giavalisco M., Dickinson M., Pettini M., 1999, ApJ 519, 1
Steidel C., Adelberger K., Shapley A., Pettini M., Dickinson M., Giavalisco M., 2003, ApJ, 592, 728
Tacconi L. et al., 2006, ApJ, 640, 228
Tacconi L. et al., 2008, ApJ, 680, 246
van Dokkum P. et al., 2008, ApJ, 677, L5
Wang W.-H., Cowie L. L., Barger A. J., 2006, ApJ, 647, 74
Webb T. et al., 2003, ApJ, 582, 6
Wehner E. H., Barger A. J., Kneib J.-P., 2002, ApJ, 577, L83

This paper has been typeset from a TEX/LATEX file prepared by the author.