A direct calibration of the IRX–$\beta$ relation in Lyman-break Galaxies at $z = 3–5$

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ABSTRACT

We use a sample of 4209 Lyman-break galaxies (LBGs) at $z \simeq 3, 4, \text{ and } 5$ in the UKIRT Infrared Deep Sky Survey Ultra Deep Survey field to investigate the relationship between the observed slope of the stellar continuum emission in the ultraviolet, $\beta$, and the thermal dust emission, as quantified via the so-called ‘infrared excess’ (IRX $\equiv L_{IR}/L_{UV}$). Through a stacking analysis, we directly measure the 850-$\upmu$m flux density of LBGs in our deep (0.9 mJy) James Clerk Maxwell Telescope SCUBA-2 850-$\upmu$m map as well as deep public Herschel/SPIRE 250-, 350-, and 500-$\upmu$m imaging. We establish functional forms for the IRX–$\beta$ relation to $z \sim 5$, confirming that there is no significant redshift evolution of the relation, and that the resulting average IRX–$\beta$ curve is consistent with a Calzetti-like attenuation law. Comparing our results with recent works in the literature, we confirm that discrepancies in the slope of the IRX–$\beta$ relation are driven by biases in the methodology used to determine the ultraviolet slopes. Consistent results are found when IRX–$\beta$ is evaluated by stacking in bins of stellar mass, and we argue that the near-linear IRX–$M_*$ relationship is a better proxy for correcting observed ultraviolet luminosities to total star formation rates, provided an accurate handle on $M_*$, and also gives clues as to the physical driver of the role of dust-obscured star formation in high-redshift galaxies.

Key words: dust, extinction – galaxies: high-redshift – galaxies: ISM – galaxies: star formation – cosmology: observations.

1 INTRODUCTION

Understanding the evolution of the star formation rate density (SFRD) with cosmic time has long been the cornerstone of ex-
tragalactic astrophysics (e.g. Madau & Dickinson 2014). At $z > 2$, most studies of the evolution of the SFRD are based on samples of Lyman-break galaxies (LBGs), due in part because of the efficiency of their selection technique in deep broad-band imaging surveys.

As a result, LBGs have been extensively studied and well characterized over the past two decades. They have stellar masses $\sim 10^{10-11} M_\odot$ and star formation rates (SFRs) $\sim 10-100 M_\odot$ yr$^{-1}$ (e.g. Madau et al. 1996; Steidel et al. 1996; Sawicki & Yee 1998; Shapley et al. 2001; Giavalisco 2003; Blaizot et al. 2004; Shapley et al. 2005; Reddy et al. 2006; Rigopoulou et al. 2006; Verma et al. 2007; Magdis et al. 2008; Chapman & Casey 2009; Lo Faro et al. 2009; Stark et al. 2009; Magdis et al. 2010; Pentericci et al. 2010; Rigopoulou et al. 2010; Bian et al. 2013; Oteo et al. 2013). LBGs are therefore believed to be responsible for forming a substantial fraction of massive local galaxies ($L > L^*$; e.g. Somerville, Primack & Faber 2001; Baugh et al. 2005), while those with the highest SFRs ($> 100 M_\odot$ yr$^{-1}$) could be the progenitors of present-day ellipticals (e.g. Verma et al. 2007; Reddy & Steidel 2009; Stark et al. 2009).

Naturally, given their selection, the most common tracer of LBGs' SFRs has traditionally been through their IR-UV star formation continuum emission (e.g. Kennicut & Evans 2012). However, it is now well known that about half of the starlight in the Universe is absorbed by interstellar dust and re-emitted in the rest-frame far-infrared (e.g. Dole et al. 2006). It is therefore necessary to complement UV-derived SFRs with far-infrared and sub-millimetre observations to obtain a full census of star formation, with the latter providing the most efficient probe of thermal dust emission out to high redshift owing to the negative k-correction. Unfortunately, typical LBGs are faint in the sub-millimetre, far below the confusion limit of most single-dish sub-millimetre facilities and challenging even for sensitive interferometric facilities such as the Atacama Large Millimetre/sub-millimetre Array (ALMA; Chapman et al. 2000; Capak et al. 2015; Bouwens et al. 2016; Kowprowski et al. 2016; Dunlop et al. 2017; McLure et al. 2018). As a result, representative samples of sub-millimetre-detected LBGs are not available.

Without direct detection of the obscured star formation in individual LBGs, empirical recipes are used to correct UV-derived SFRs to total SFRs. The most common approach is to use the relationship between the rest-frame UV slope, $\beta$, where $f_\beta \propto \lambda^\beta$, and the infrared excess, IRX $\equiv L_{IR}/L_{UV}$ (Meurer, Heckman & Calzetti 1999). Overzier et al. (2011) found that local analogues of LBGs are consistent with the Meurer et al. (1999) relation, while at $z > 3$ Coppin et al. (2015) and Alvarez-Márquez et al. (2016) found LBGs to be lying above and below the local relation, respectively. Recently, McLure et al. (2018) showed that the IRX$-\beta$ relation for $z \sim 3$ galaxies is consistent with a Calzetti-like attenuation law (Calzetti et al. 2000), while Reddy et al. (2018) suggest that a flatter, Small Magellanic Cloud (SMC)-like curve should be applied. In addition, a number of individual direct detections for LBGs and infrared-selected galaxies have been found to exhibit a large scatter in the IRX$-\beta$ plane (e.g. Casey et al. 2014; Capak et al. 2015; Kowprowski et al. 2016; Scoville et al. 2016; Fudamoto et al. 2017). It remains unclear whether these inconsistencies are due to intrinsic scatter in the IRX$-\beta$ relation or biases in the selection and measurement techniques. It is therefore necessary to perform a critical analysis at these high redshifts, utilizing a large, unbiased sample of galaxies.

In this paper, we use 4209 LBGs at redshifts $3 < z < 5$ in the UKIRT Infrared Deep Sky Survey (UKIDSS)/Ultra-Deep Survey (UDS) field, stellar mass complete down to a limit of $\log(M_*/M_\odot) \geq 10.0$, to establish the IRX$-\beta$ relation. We are able to determine the IR luminosities for these galaxies through stacking in a deep JCMT SCUBA-2 850-µm map from the SCUBA-2 Cosmology Legacy Survey (S2CLS; Geach et al. 2017), and 350–500 µm SPIRE mapping from the Herschel Space Observatory. This paper expands on the work of Coppin et al. (2015), with a $2 \times$ deeper SCUBA-2 map of UDS, now approaching the SCUBA-2 confusion limit (with a 1σ depth of 0.9 mJy beam$^{-1}$) as well as improved methodology for determining UV slopes and a clearer LBG sample. With this sample, we are able to calibrate the IRX$-\beta$ relationship out to redshifts as high as $z \sim 5$ and therefore determine the average dust properties of star-forming galaxies, which are much less prone to selection biases characteristic of small samples at these early times (e.g. Capak et al. 2015). Section 2 summarizes the data used and explains our LBG selection criteria. In Section 3, we explain how the spectral energy distribution (SED) fitting is performed and derive the basic physical properties of galaxies in the sample. In Section 4, we measure the IRX$-\beta$ relation for LBGs at $z = 3, 4, 5$ and explain its physical origin, comparing our findings with other results from the literature. We present our conclusions in Section 5.

Throughout, magnitudes are quoted in the AB system (Oke & Gunn 1983), and we use the Chabrier (2003) stellar initial mass function (IMF). We assume a cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. We note that assuming the best-fitting Planck Collaboration XIII (2016) cosmology yields $\pm 2$–2.5 per cent higher luminosity distances, and hence $\pm 4$–5 per cent higher stellar masses and luminosities.

2 DATA

2.1 Optical & near-IR imaging

Our sample is drawn from the deep K-band image of the UKIDSS (Lawrence et al. 2007), UDS$^1$ data release 8 (DR8), together with the available multiwavelength photometry. The UDS is the deepest of the five UKIDSS sub-surveys (Almaini et al., in preparation), covering 0.77 deg$^2$ in the second was optimized to detect resolved galaxies (see Hartley et al. 2013 for details). The UKIDSS UDS has also been imaged by the Canada–France–Hawaii Telescope (CFHT) Megacam U-band (26.75 mag), Subaru Suprime-cam ($B = 27.6, V = 27.2, R = 27.0, i = 27.0, z = 26.0$; Furusawa et al. 2008), and the Spitzer Infrared Array Camera (IRAC; Fazio et al. 2004, [3.6µm] = 24.2 and [4.5µm] = 24.0), as a part of the UDS Spitzer Legacy Program (SpUDS; PI: Dunlop). To remove obvious active galactic nuclei (AGN), X-ray (Ueda et al. 2008) and radio (Simpson et al. 2006) data were used. The total coincident area of these data sets is 0.62 deg$^2$. All images were astrometrically aligned and multiband photometry extracted in 3-arcsec diameter apertures at the positions of K-band detections (see Simpson et al. 2012 for details), including point- spread function corrections where appropriate (Hartley et al. 2013).

2.1.1 LBG selection

The LBG selection technique relies on the fact that photons with energies higher than the rest-frame 1216 Å are almost entirely

\footnote{http://www.nottingham.ac.uk/astronomy/UDS/}
absorbed by the neutral gas around the star-forming regions in the galaxy, resulting in a characteristic break that is easily identified with broad-band colours. This technique is used to identify galaxies at $z \approx 3$ using UGR, or BVR filters (Steidel et al. 1996) but can be easily extended to higher redshifts by simply shifting the colour space to longer wavelengths, as described by Ouchi et al. (2004). In this work, we use the following selections for LBGs at $z \approx 3$ (equation 1), $z \approx 4$ (equation 2), and $z \approx 5$ (equations 3 and 4):

$$R < 27, \quad (U-V) > 1.2,$$
$$-1.0 < (V-R) < 0.6, \quad (U-V) > 3.8(V-R) + 1.2; \quad (1)$$

$$i' < 27, \quad (B-R) > 1.2,$$
$$\quad (R-i') < 0.7, \quad (B-R) > 1.6(R-i') + 1.9; \quad (2)$$

$$z' < 26, \quad (V-i') > 1.2,$$
$$\quad (i'-z') < 0.7, \quad (V-i') > 1.8(i'-z') + 2.3; \quad (3)$$

$$z < 26, \quad (R-i') > 1.2,$$
$$\quad (R-i') > (i'-z') + 1.0, \quad (4)$$

where $z \approx 5$ LBGs are identified using either equations (3) or (4) in order to maximize our yield (see Ouchi et al. 2004). Note that since the parent optical catalogue is selected at K-band ($K < 24.6$), our resulting LBG sample is mass complete to a limit of $\log(M_{*}/M_{\odot}) \geq 10.0$.

Photometric redshifts are determined for each source in our parent catalogue using 11 photometry bands (UBVRI $z$ JHK[3.6][4.5]), as described in Hartley et al. (2013) and Mortlock et al. (2013), using the EAZY template-fitting code. Six SED templates were used (Brammer, van Dokkum & Coppi 2008), with the bluest template having an SMC-like extinction added. The accuracy of the photometric redshifts is assessed by comparing with the available spectroscopic data, as described in Hartley et al. (2013), with the average $|z_{\text{phot}} - z_{\text{spec}}|/(1 + z_{\text{spec}}) = 0.031$.

To help eliminate low-redshift interlopers in the LBG selections, we initially enforce the minimum best-fitting (i.e. peak of the redshift probability density distribution) redshift to be $z = 2$. In the left-hand panel of Fig. 1, the normalized sum of the redshift probability distributions is shown for each redshift selection, indicating peaks at 3.35, 3.87, and 4.79. Thus, the selection criteria used here are given in Geach et al. (2017), but the map spans 1 deg centred on the UDS and reaches a uniform depth of 0.9 mJy beam$^{-1}$. Note that this final map is a factor of 2 deeper than the map used in Coppin et al. (2015).

Similarly to SPIRE maps, we have decided to subtract all SCUBA-2 sources with the signal-to-noise ratio of $>3.5$ from the 850-μm maps, which were not associated with our sample. To identify the 850-μm counterparts to our LBGs, we have used the high-resolution ALMA follow-up observations of all the SCUBA-2 sources in the UDS field (PI: Small), where 36 ALMA-detected LBGs were found. We note that the detailed evaluation of the ALMA-detected LBGs will be presented in Koprivschi et al. (in preparation). The resulting stacks of the median stacks at each redshift bin are shown in Fig. 2, and the corresponding numbers summarized in Table 1. We find $12.0 \sigma, 11.0 \sigma$, and $3.8 \sigma$ detections in the $z \approx 3, z \approx 4$, and $z \approx 5$ redshift bins, respectively.

Fig. 3 shows the average radial profile of the $z \approx 3$ stack compared to the SCUBA-2 beam (which differs slightly from a pure Gaussian). The stacked profile is indistinguishable from the shape of the beam and therefore any clustering of the sources associated with the LBGs that also contribute to the 850-μm flux density (Chary & Pope 2010; Kurczynski & Gawiser 2010; Serjeant et al. 2010) is on scales unresolved by SCUBA-2; i.e. below approximately 15 arcsec or 120 kpc. We ignore this potential contribution in the following analysis and consider the average sub-millimetre emission as coming from the LBG itself.

## 3 RESULTS

### 3.1 SED fitting

To fit the stacked flux densities, we use 185 SED templates compiled by Swinbank et al. (2014). These include local galaxy templates from Chary & Elbaz (2001), Rieke et al. (2009), and Draine et al. (2007) as well as high-redshift starburst galaxies from Ivison et al. (2010) and Carilli et al. (2011), with a range of dust temperatures spanning 19–60 K. With redshifts fixed at the peak values from Table 1, we find the best-fitting SEDs using a standard $\chi^2$ minimization approach. At $z = 4.79$, only the 850-μm stacked flux density was detected at $>3\sigma$, and so here, we adopt our $z = 3.87$ best-fitting SED redshifted to $z = 4.79$ and normalized to the 850-μm flux. The fits have a consistent temperature of $T_d \approx 40$ K.

We also determine the best-fitting rest-frame UV-to-millimetre model SEDs, where the UV-through-near-IR photometry and un-
Figure 1. Redshift probability distributions with the corresponding most probable redshifts shown in the legend. Left: Redshift probability distributions for the LBG selection criteria from equations (1)–(4), with the additional constraint of $z > 2$ in place. It can be seen that the resulting most probable redshifts are close to the target values of 3, 4, and 5. However, the distributions show a low-redshift peak at $z \simeq 2.5$, this being the result of a number of contaminating galaxies being included using our selection criteria. Right: Since the $z \simeq 2.5$ sources from the left-hand panel will contaminate the inferred values of the stellar masses as well as UV slopes, we decided to introduce an additional selection criteria, where we force the best-fitting redshifts to be $>2.5, >3,$ and $>4$ for the $z \sim 3, z \sim 4,$ and $z \sim 5$ samples, respectively. This panel shows the resulting redshift probability distributions. Note that the low-redshift peaks at $z \sim 0.5$ do not result from a number of sources being found at low redshifts but rather from a small number of individual probability distributions being double-peaked (with the low-$z$ solution having lower probability).

Table 1. Stacked IR-sub-millimetre photometry for LBGs. The columns show the most probable redshift in each bin, the number of selected LBGs, and the stacked photometry in the Herschel SPIRE and JCMT SCUBA-2 850-μm bands, with $1\sigma$ errors and detection significance in brackets.

<table>
<thead>
<tr>
<th>⟨z_{phot}⟩</th>
<th>N</th>
<th>$S_{250}$/mJy</th>
<th>$S_{350}$/mJy</th>
<th>$S_{500}$/mJy</th>
<th>$S_{850}$/mJy</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.35</td>
<td>3439</td>
<td>0.43 ± 0.03 (14.3σ)</td>
<td>0.77 ± 0.04 (19.3σ)</td>
<td>0.39 ± 0.04 (9.8σ)</td>
<td>0.12 ± 0.01 (12.0σ)</td>
</tr>
<tr>
<td>3.87</td>
<td>710</td>
<td>0.51 ± 0.07 (7.3σ)</td>
<td>0.77 ± 0.09 (8.6σ)</td>
<td>0.53 ± 0.09 (5.9σ)</td>
<td>0.33 ± 0.03 (11.0σ)</td>
</tr>
<tr>
<td>4.79</td>
<td>60</td>
<td>0.34 ± 0.26 (1.3σ)</td>
<td>0.41 ± 0.38 (1.1σ)</td>
<td>0.31 ± 0.27 (1.1σ)</td>
<td>0.30 ± 0.08 (3.8σ)</td>
</tr>
</tbody>
</table>

Figure 2. 60 arcsec × 60 arcsec stamps of the median stacks at SCUBA-2 850-μm maps for each redshift bin, centred on the LBG positions. The resulting numbers are summarized in Table 1.

The SFR on time is

$$\Psi(t) \propto \exp(-t_1/\tau_1) + f_m\exp(-t_2/\tau_2),$$

with $\tau_1, \tau_2,$ and the mass fraction of the late burst population, $f_m,$ being free parameters. This allows a large variation of SFH, allowing for both single-burst and double-burst, instantaneous, exponentially declining, and continuous histories. To implement the dust attenuation, the two most extreme cases of Calzetti et al. (2000) attenuation curve and SMC-like extinction curve (Gordon et al. 2003)

2http://cigale.lam.fr/
were used. Finally, the thermal dust emission was modelled with the modified grey bodies of Casey (2012), where the mid-infrared power-law slope and dust emissivity index are fixed at 2.6 and 1.6, respectively, while the temperature is allowed to vary between 20 and 80 K. The best-fitting SEDs are plotted in Fig. 4 as black curves. Since CIGALE uses energy balance, the unattenuated stellar emission SEDs can be estimated for each of the adopted attenuation/extinction curves, which we show in Fig. 4 as blue solid and brown dashed lines, for the Calzetti et al. (2000) attenuation and SMC-like extinction curves, respectively.

3.2 UV & IR luminosities and stellar masses

The CIGALE fits described above are used to estimate the average stellar mass of each sample. As noted by Dunlop (2011), the use of a multicomponent SFH generally leads to more accurate values of stellar mass than the use of a single SFH. This is due to the fact that in a single-burst scenario the entire stellar population must be young in order to reproduce the UV emission, thus the less massive but more abundant old stars are often not properly accounted for (see also Michalowski et al. 2012, 2014). The stellar mass distributions corresponding mean values for each redshift bin are shown in Fig. 5, with the numbers summarized in Table 2. The average stellar mass increases with redshift, which is a simple consequence of the NIR selection limit for our parent catalogue (Section 2.1), as shown in Fig. 6. For the same reason, our K-band-limited sample is only complete to a stellar mass limit of log($M_*/M_\odot$) $\geq$ 10.0 (see Fig. 6).

The UV luminosity is defined here as $L_{UV} \equiv \nu_{1600}L_{1600}$, where the luminosity density at rest-frame 1600 Å, $L_{1600}$, is determined from the best-fitting SED. The luminosity distributions are shown in the right-hand panel of Fig. 5, with the mean values summarized in Table 2. Again, $L_{UV}$ is increasing with redshift, which, as in the case of the stellar mass, is a result of the fixed optical flux limits in the LBG selection. While the difference between $z = 3.35$ and $z = 3.87$ is small ($R < 27$ and $i < 27$ from equations 1 and 2, respectively), the UV luminosity for $z = 4.79$ is significantly higher because the corresponding rest-frame UV imaging is shallower ($\mu < 26$, equations 3 and 4).

Finally, total IR luminosities are determined by integrating under the best-fitting IR SED between rest-frame 8 and 1000 μm (Table 2). Again, average $L_{IR}$ increases with redshift, which is most likely linked to the increase in stellar mass rather than a real evolutionary trend.

4 ANALYSIS AND DISCUSSION

4.1 IRX–β relation

4.1.1 UV slopes

Several different techniques have been used in the literature to measure the UV slope, $\beta$ (see Rogers, McLure & Dunlop 2013 for a review). The original work of Meurer et al. (1999) fitted a simple power-law to the 10 continuum bands listed by Calzetti, Kinney & Storchi-Bergmann (1994) in the rest-frame range of $\sim$1250–2500 Å. In most cases, however, only a few bands are available in that range, introducing uncertainty on $\beta$. In addition, the possible existence of the 2175-Å feature in the dust attenuation curve can potentially impact the inferred values of the photometry-based UV slopes, driving up scatter in $\beta$. As shown by McLure et al. (2018) and explained further next, this scatter is significant enough to cause a bias that serves to flatten the IRX–$\beta$ relation. To try to minimize these effects, we measure $\beta$ by fitting a power-law to the best-fitting SED over a rest-frame range of 1250–2500 Å rather than the photometry directly.

4.1.2 Stacking IRX

To measure the average IRX $\equiv L_{IR}/L_{UV}$, we first bin the sample in $\beta$. We do not a priori know how $L_{IR}$ couples with $L_{UV}$, so we cannot assume that the IRX in each $\beta$ bin is simply equal to $(L_{IR}/L_{UV})$. Therefore, we cannot stack the 850-μm flux densities (i.e. $L_{850}$) and divide by the mean $L_{UV}$. Instead, we follow Bourne et al. (2017) by assuming that (IRX) $\equiv (L_{IR}/L_{UV})$, stacking individual values of IRX, which is more directly comparable to individually detected galaxies in the IR (eg. Capak et al. 2015; Kozowski et al. 2016). We find the individual values of $L_{IR}$ assuming all LBGs are described by the average best-fitting template and normalize this to the observed 850-μm flux density at the position of each galaxy. Uncertainties on individual $L_{IR}$ are estimated from the same measurement in noise-only maps at 850 μm using the same scaling factor. The results are presented in Fig. 7 and Table 3.

We stress that the individual values of IRX and $\beta$ have been calculated independently, and that we did not use the energy balance available in CIGALE. The $L_{IR}$ for each LBG was found from the best-fitting empirical dust-emission SEDs (red curves in Fig. 4), while the $L_{UV}$ and $\beta$ were determined from the best-fitting SED to the rest-frame UV-NIR photometry available for each of the sources in our sample. We also note that the choice of the attenuation/extinction curve only affects the shape of the resulting intrinsic stellar SEDs (blue solid and brown dashed curves in Fig. 4) and has no effect on the inferred values of the observed UV slopes.

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3Note that the dust temperature in the Casey (2012) models is an effective temperature, which is numerically higher than the temperature normally quoted in the literature, $T_d$, corresponding to the peak of the thermal infrared emission (see Fig. 2 in Casey 2012).
Figure 4. Best-fitting SEDs at rest-frame wavelengths for the stacked results in each redshift bin. The IR photometry comes from stacking LBGs in Herschel SPIRE and JCMT SCUBA-2 850-μm bands, while the rest-frame UV-NIR photometry points are median values from all the LBGs in a given redshift bin, with the errors being median absolute deviations. The red curves (used in the calculations of $L_{\text{IR}}$) are best-fitting empirical IR SEDs of Swinbank et al. (2014) found using a $\chi^2$ minimization method. In addition, we plot in black the best-fitting rest-frame UV-millimetre SEDs found using CIGALE, where Bruzual & Charlot (2003) stellar population templates, Chabrier (2003) IMF, and the thermal-dust-emission model of Casey (2012) were adopted (see Section 3.1 for details). For the dust attenuation, the two most extreme cases of Calzetti et al. (2000) and SMC (Gordon et al. 2003) were used, with the corresponding unattenuated stellar emission SED shown with blue solid and brown dashed lines, respectively.

4.1.3 Functional form of IRX–$\beta$ relation

We adopt a functional form of IRX from Meurer et al. (1999)

$$\text{IRX} = (10^{0.4A_{1600}} - 1) \times B,$$

(6) \hspace{1cm} B = \frac{BC(1600)}{BC(\text{FIR})}. \hspace{1cm} (7)

where $A_{1600}$ is the attenuation at the rest-frame 1600 Å in magnitudes and $B$ is the ratio of two bolometric corrections.
Figure 5. Left: Histogram of stellar masses for each redshift bin found from the best-fitting rest-frame UV-NIR SEDs (see Section 3.2 for details). It can be seen that the masses increase with redshift, which is a consequence of the selection limit for our parent catalogue of \( K < 24.6 \). Since we can treat \( K \)-band as a rough proxy for the stellar mass (see Fig. 6), we expect the average mass to increase with redshift due to the positive \( K \)-correction in this band. The grey dashed line marks the mass limit down to which our LBG sample is complete. This is a consequence of our parent optical catalogue being selected at \( K \)-band (see also Fig. 6). Right: Histogram of the UV luminosities for each redshift bin in this work. As in the case of the stellar masses, the UV luminosities tend to increase with redshift. Again, this is caused by the depth of our parent catalogue in the rest-frame UV bands.

Table 2. Physical properties for LBGs. The stellar masses and UV luminosities are mean values in each bin (see Fig. 5), with the errors being standard deviations rather than the errors on the mean (gives indication of the scatter). The IR luminosities are found by integrating the best-fitting empirical IR templates (red curves in Fig. 4) between 8 and 1000 \( \mu m \).

<table>
<thead>
<tr>
<th>( z )</th>
<th>( \log(M_*/M_\odot) )</th>
<th>( \log(L_{UV}/L_\odot) )</th>
<th>( \log(L_{IR}/L_\odot) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.35</td>
<td>9.78 ± 0.45</td>
<td>10.51 ± 0.25</td>
<td>11.37 ± 0.02</td>
</tr>
<tr>
<td>3.87</td>
<td>9.89 ± 0.38</td>
<td>10.65 ± 0.27</td>
<td>11.61 ± 0.03</td>
</tr>
<tr>
<td>4.79</td>
<td>10.00 ± 0.27</td>
<td>10.85 ± 0.17</td>
<td>11.59 ± 0.10</td>
</tr>
</tbody>
</table>

The original Meurer et al. (1999) relation was defined as IRX \( \equiv L_{FIR}/L_{UV} \), where

\[
L_{FIR} = 1.25(L_{60} + L_{100}),
\]

with \( L_{60} \) and \( L_{100} \) are the luminosities measured by \( \text{IRAS} \) at 60 and 100 \( \mu m \). To correct from \( L_{FIR} \) to total bolometric IR luminosity, the BC(\( 1600 \)) correction was needed. Here, we defined IRX as \( L_{60}/L_{UV} \), so the IR bolometric correction factor, BC(\( 1600 \)), is by definition equal to unity. The UV bolometric correction, BC(\( 1600 \)), converts between all the stellar light available to heat the dust and the intrinsic \( F_{1600} \) measured at the rest-frame 1600 \( \AA \). This can be calculated once the intrinsic stellar-emission SED is known by integrating between the 912 \( \AA \) (Lyman limit) and infinity. As explained above, we consider the two most extreme cases of a Calzetti et al. (2000) attenuation curve and an SMC-like extinction curve (Gordon et al. 2003).

To find the average intrinsic stellar emission SED corresponding to each of the attenuation/extinction curves, we used the energy balance feature of CIGALE, where the amount of the stellar light attenuated by dust is assumed to be equal to the light re-emitted in the IR (Table 2). The resulting UV bolometric corrections, BC(\( 1600 \)), and the intrinsic UV slopes, \( \beta_{int} \), for both attenuation/extinction curves for each redshift bin are given in Table 4.

The attenuation at 1600 \( \AA \), \( A_{1600} \), from equation \( (6) \), can be described as

\[
A_{1600} = \frac{\delta A_{1600}}{\delta \beta} (\beta_{obs} - \beta_{int}),
\]

where \( \delta A_{1600}/\delta \beta \) is the slope of the reddening law, and \( \beta_{obs} \) and \( \beta_{int} \) are the observed and the intrinsic UV slopes, respectively. To find the slope of the reddening law for the Calzetti- and SMC-like curves, we reden an intrinsic (dust unattenuated) stellar SED (blue curves in Fig. 4) in small steps and calculate the amount of the attenuated stellar light. This is then equated with the energy re-emitted in the IR by dust. The results of this exercise are depicted in Fig. 8, where we find slopes of 2.1 for the Calzetti- and 0.9 for the SMC-like dust.

The resulting functional forms of the IRX–\( \beta \) relations (equations \( 6, 7, \) and \( 9 \)) for each attenuation/extinction curve in each redshift bin are summarized in Table 4 and plotted in Fig. 7. It is clear from Fig. 7, that our data are consistent with Calzetti-like dust attenuation (similar to McLure et al. 2018 find at \( z \sim 3 \)), and that there is no significant evolution of the IRX–\( \beta \) relation with redshift, as found for the sub-millimetre bright SCUBA-2 galaxies by Bourne.
et al. (2017). It is also clear from Fig. 8 that galaxies following a given IRX–β relation have on average similar intrinsic UV slopes with similar corresponding stellar populations, consistent with the models of Narayanan et al. (2018), Popping, Puglisi & Norman (2017), and Safarzadeh, Hayward & Ferguson (2017).

4.2 Comparison with recent studies

In Fig. 9, we compare our $z = 3.35$ results with others works: Heinis et al. (2013), Álvarez-Márquez et al. (2016), Reddy et al. (2018), and McLure et al. (2018). Solid and dashed black lines represent the functional forms of the IRX–β relation for Calzetti-like atten-
...mass bin upper limit is the only mass-incomplete data point (see mass bin is the mean with the error being the standard error on the mean. The stellar mass in each stellar mass bin is the mean with the error being the standard error on the mean. The lowest mass bin upper limit is the only mass-incomplete data point (see Fig. 6).

<table>
<thead>
<tr>
<th>Sample</th>
<th>N</th>
<th>(IRX)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$ bins :</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$z = 3.35$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta = -2.00$</td>
<td>1523</td>
<td>$&lt;2.11$</td>
</tr>
<tr>
<td>$\beta = -1.63$</td>
<td>1422</td>
<td>$7.25 \pm 0.94$</td>
</tr>
<tr>
<td>$\beta = -1.09$</td>
<td>315</td>
<td>$19.97 \pm 3.71$</td>
</tr>
<tr>
<td>$\beta = -0.57$</td>
<td>115</td>
<td>$95.70 \pm 8.81$</td>
</tr>
<tr>
<td>$\beta = -0.02$</td>
<td>43</td>
<td>$110.21 \pm 23.92$</td>
</tr>
<tr>
<td>$z = 3.87$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$\beta = -1.93$</td>
<td>228</td>
<td>$2.63 \pm 0.83$</td>
</tr>
<tr>
<td>$\beta = -1.57$</td>
<td>353</td>
<td>$9.02 \pm 0.97$</td>
</tr>
<tr>
<td>$\beta = -1.02$</td>
<td>85</td>
<td>$19.85 \pm 2.94$</td>
</tr>
<tr>
<td>$\beta = -0.47$</td>
<td>31</td>
<td>$22.92 \pm 4.74$</td>
</tr>
<tr>
<td>$z = 4.79$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$\beta = -1.74$</td>
<td>50</td>
<td>$&lt;4.47$</td>
</tr>
<tr>
<td>$\beta = -1.11$</td>
<td>7</td>
<td>$29.58 \pm 5.83$</td>
</tr>
</tbody>
</table>

$log(M_*/M_\odot) = 9.47 \pm 0.13$ 1339 $<2.30$
$log(M_*/M_\odot) = 9.90 \pm 0.13$ 1635 $4.71 \pm 0.67$
$log(M_*/M_\odot) = 10.33 \pm 0.13$ 722 $20.39 \pm 1.30$
$log(M_*/M_\odot) = 10.81 \pm 0.13$ 176 $34.93 \pm 3.73$

Table 4. Functional forms of the IRX–$\beta$ relation for Calzetti-like attenuation and SMC-like extinction curves (see Section 4.1.3 for details) plotted in Fig. 7.

<table>
<thead>
<tr>
<th>$z$</th>
<th>IRX</th>
<th>$A_{1600}$</th>
</tr>
</thead>
</table>
| 3.35 | $(1.56 \pm 0.07) \times 10^{0.44_{1600}} - 1$ | $2.10(\beta + (2.31 \pm 0.07))$
| 3.87 | $(1.56 \pm 0.06) \times 10^{0.44_{1600}} - 1$ | $2.10(\beta + (2.29 \pm 0.07))$
| 4.79 | $(1.62 \pm 0.10) \times 10^{0.44_{1600}} - 1$ | $2.10(\beta + (2.25 \pm 0.09))$

<table>
<thead>
<tr>
<th>$z$</th>
<th>IRX</th>
<th>$A_{1600}$</th>
</tr>
</thead>
</table>
| 3.35 | $(1.54 \pm 0.05) \times 10^{0.44_{1600}} - 1$ | $0.92(\beta + (2.34 \pm 0.04))$
| 3.87 | $(1.52 \pm 0.04) \times 10^{0.44_{1600}} - 1$ | $0.92(\beta + (2.34 \pm 0.04))$
| 4.79 | $(1.53 \pm 0.04) \times 10^{0.44_{1600}} - 1$ | $0.92(\beta + (2.29 \pm 0.04))$

To investigate the effects of the scatter of the photometry-based UV slopes about their real values on the resulting shape of the IRX–$\beta$ relation, we have re-stacked our $z = 3.35$ data. To estimate the UV slope for each galaxy, we fit a simple power-law to the photometry available in the rest-frame range of 1250–2500 Å and then stack the IRX in the same $\beta$ bins as in Section 4.1.2. The results are shown in Fig. 9 as white circles. It can be seen that at the red end, IRX values are suppressed, effectively flattening to relation, and pushing towards the SMC-like curve. This is because, with our present data, we only have three continuum bands in the rest-frame range of 1250–2500 Å, resulting in larger errors on $\beta$ and therefore more scatter in individual $\beta$ bins. Using power-law fits to the corresponding rest-frame UV range in the best-fitting SEDs, using all 11 bands of observational data (even if this is not in the nominal range for a direct estimate of $\beta$), significantly reduces this scatter.

Another approach, taken by McLure et al. (2018), is to bin the sample in stellar mass. This is motivated by the growing consensus that it is the total stellar mass that influences the amount of the dust extinction (Heinis et al. 2013; Álvarez-Márquez et al. 2016; Dunlop et al. 2017; Reddy et al. 2018). We show the stellar mass-binned results of McLure et al. (2018) in Fig. 9 as red circles. It clearly shows, consistent with this work, that $z \sim 3$ LBGs are affected by dust extinction characteristics of the Calzetti et al. (2000) law. With $M_*$ being a more fundamental parameter, often the dependence of IRX on $M_*$ is determined, instead of UV slope. To this end, we stack the $z \sim 3$ sample in bins of $M_*$. The results are shown in Fig. 10 as black circles, with a best-fitting power-law curve of

$$log(IRX) = (0.87 \pm 0.10) \times log(M_*/10^{10}M_\odot) + (0.98 \pm 0.04),$$

and the grey area depicting 1σ uncertainties. Our results are in excellent agreement with McLure et al. (2018), who find a virtually identical form, with a slope of 0.85 ± 0.05 and zero-point of 0.99 ± 0.03. We also compare other results in the literature corresponding to the data from Fig. 9. One can see that the inconsistencies between different works are much smaller, most likely because the...
stellar masses are in all cases determined from the best-fitting SEDs well sampled with photometry.

5 CONCLUSIONS
We have extended the work of Coppin et al. (2015) to improve on and calibrate the IRX–β relation at $z \simeq 3$–5 using 4178 LBGs, stellar mass complete down to a limit of $\log(M_*/M_\odot) \gtrsim 10.0$. We are able to determine the average total IR luminosity by stacking galaxies in deep SCUBA-2 850 μm and SPIRE 250–500 μm imaging. By evaluating the observed UV slope, β, and emergent UV luminosity, we investigate the infrared excess, IRX, as a function of observed UV slope and stellar mass, deriving functional forms. We conclude the following:

(i) $3 < z < 5$ LBGs are consistent with the Calzetti et al. (2000) attenuation law, consistent with the findings of McLure et al. (2018), Cullen et al. (2017), and Cullen et al. (2018) at $z \sim 3$, now extended...
to $z \sim 5$. This describes a scenario, where dust and stars are ‘well mixed,’ on average. In addition, similarly to Bourne et al. (2017), we find no significant redshift evolution in the IRX–$\beta$ over $z \approx 3$–5.

(ii) The IRX–$\beta$ relationship for LBGs in our sample is characteristic of galaxies with similar stellar population ages, corresponding to similar intrinsic UV slopes ($\beta_{\text{int}} \sim -2.3$), such that the observed value of $\beta$ is entirely driven by dust obscuration. In turn, this increases the corresponding IR luminosity, and hence the IRX. This picture is consistent with the theoretical work of Narayanan et al. (2018), Popping et al. (2017), and Safarzadeh et al. (2017).

(iii) Comparing our results with the recent literature findings of Heinis et al. (2013), Álvarez-Márquez et al. (2016), Reddy et al. (2018), and McLure et al. (2018), we find some inconsistencies, where some papers have found significantly lower IRX values for a given $\beta$, implying a more ‘SMC-like’ relation. We have confirmed that these inconsistencies are driven by scatter in measured values of $\beta$ from limited photometry that serves to artificially flatten IRX–$\beta$. The scatter is significantly reduced by determining $\beta$ from full SED fits.

(iv) Stacking IRX in bins of stellar mass, instead of as a function of $\beta$, results in a much more consistent picture. There is a tight IRX–$M_*$ relationship in which dust-reprocessed stellar emission scales nearly linearly with stellar mass. There is much better consistency across different works in this parameter space, likely due to the full SED fitting used to derive stellar masses, reducing relative uncertainties. We agree that the IRX–$M_*$ relationship is probably a far better proxy for correcting observed UV luminosities to total SFRs, provided an accurate handle on $M_*$, and also gives clues as to the physical driver of dust-obsured star formation in high-redshift galaxies.

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