The detection of FIR emission from high-redshift star-forming galaxies in the ECDF-S

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ABSTRACT

We have used the Large Apex Bolometer Camera Survey of the Extended Chandra Deep Field South to investigate rest-frame far-infrared (FIR) emission from typical star-forming systems (Lyman-break galaxies, LBGs, and Lyman α emitters, LAEs) at redshift 3, 4, 4.5 and 5 (922, 68, 46 and 20 sources, respectively). We initially concentrate on LBGs at $z \sim 3$ and select three sub-samples on stellar mass (rest-frame optical brightest, $M_\ast > 10^{10.25} M_\odot$), extinction-corrected star formation (assuming $\beta_{\text{UV}} = -2$ and applying a dust attenuation correction, $\text{SFR}_{\text{tot}} > 6.7 M_\odot \text{yr}^{-1}$) and rest-frame UV magnitude (representing a typical Lyman-break selection with $R < 24.43$). We produce composite 870 $\mu$m images of the typical source in our sub-samples, obtaining $\sim 4\sigma$ detections (0.61, 0.35 and 0.37 mJy, respectively) and suggesting a correlation between FIR luminosity and stellar mass. We apply a similar procedure to our full samples at $z \sim 3, 4, 4.5$ and 5 and do not obtain detections – a result that is consistent with a simple scaling between FIR luminosity and stellar mass. In order to constrain the FIR spectral energy distribution (SED) of these systems, we explore their emission at multiple wavelengths spanning the peak of dust emission at $z \sim 3$ using the Herschel Spectral and Photometric Imaging Receiver (SPIRE) observations of the field. We obtain detections at multiple wavelengths of both our stellar mass and UV-magnitude-selected samples, and find a best-fitting SED with dust temperatures in the $\sim 33–41$ K range. We calculate FIR luminosity, obscured star formation rates (SFRs) and dust masses and find that a significant fraction of star formation in these systems is obscured. Interestingly, our sample selected on extinction-corrected SFR does not display the large FIR fluxes predicted from its red UV spectral slope. This suggests that the method of assuming an intrinsic UV slope and correcting for dust attenuation may be invalid for this sample – and that these are not in fact the most actively star-forming systems. All of our $z \sim 3$ samples fall on the ‘main sequence’ of star-forming galaxies at $z \sim 3$ and our detected sub-samples are likely to represent the high obscuration end of the LBGs population at their epoch. We compare the FIR properties of our sub-samples with various other galaxy populations, finding that our stellar mass selected sample shows some similar FIR characteristics to Submillimeter Galaxies (SMGs) at the same epoch and therefore potentially represents the low FIR luminosity end of the high-redshift FIR luminosity function.

Key words: dust, extinction – galaxies: evolution – galaxies: high-redshift – galaxies: starburst.

1 INTRODUCTION

Lyman-break Galaxies (LBGs, e.g. Steidel, Pettini & Hamilton 1995) form a substantial fraction of the observed high-redshift ($z \gtrsim 3$) galaxy population (e.g. Steidel et al. 1995; Douglas et al. 2009, 2010; Vanzella et al. 2009). Primarily identified via bright UV emission which arises from hot, young O and B stars in relatively unobscured regions. The properties of these systems have been extensively studied via their rest-frame UV spectra and UV–optical spectral energy distributions (SEDs; e.g. Shapley et al. 2001; Rigopoulou et al. 2006; Verma et al. 2007; Stark et al. 2009). Given that in the past two decades LBG samples have dominated observational studies of galaxies at $z > 3$ it is unfortunate that comparatively little work has been carried out to explore the properties of their non-optical/UV-bright components (interstellar gas and cool dust), which are necessary for a more complete picture of
these early star-forming systems. If we wish to build a comprehensive understanding of star formation activity and galactic evolution in high-redshift systems we must observe their complete baryonic budget of stellar material, dust and molecular gas. Through a detailed comparison of the stellar, molecular gas and dust fractions we can infer their star formation history and potential fate – thereby investigating their importance to the evolution of galaxies in general. In our previous studies, we have investigated the molecular gas and dust content of \( z \sim 5 \) LBGs (Stanway, Bremer & Lehnert 2008; Stanway et al. 2010; Davies et al. 2010, 2012b), here we expand this work to consider the dust content of LBGs over a range of epochs.

Several observational studies have attempted to constrain the dust content of \( z \gtrsim 3 \) star-forming galaxies (e.g. Chapman et al. 2000; Webb et al. 2003; Carilli et al. 2007; Chapman & Casey 2009; Stanway et al. 2010; Davies et al. 2012b; Lee et al. 2012; Oteo et al. 2013). In combination, these works have determined that typical LBGs have relatively faint far-infrared (FIR) luminosities \((L_{\text{FIR}} \lesssim 10^{11} \, L_{\odot})\) and therefore low dust masses \((M_{\text{dust}} \lesssim 10^3 \, M_{\odot})\) – for reasonable assumptions of dust temperature and SED. While these studies have produced relatively tight constraints on the FIR emission from these sources, the small number of galaxies targeted, up to \( \sim 140 \) photometrically selected objects at \( z \sim 3 \) (Webb et al. 2003) and \( \sim 20 \) spectroscopically confirmed sources at \( z \sim 5 \) (Stanway et al. 2010; Davies et al. 2012b), limits the depth of any combined image used to determine their typical FIR properties \((\gtrsim 0.5 \, mJy \, beam^{-1} \text{ at } 870 \, \mu m)\). Some individual detections have been achieved by targeting highly lensed LBGs at \( z \sim 3, \) typically obtaining unlensed \( 850 \, \mu m \) fluxes of \(<0.8 \, mJy\) (e.g. Baker et al. 2001; Chapman et al. 2002; Borys et al. 2004; Kneib et al. 2005; Coppin et al. 2007; Siana et al. 2009; Negrello et al. 2010; Conley et al. 2011, and see Chapman & Casey 2009 for a summary). In addition, Baker et al. (2001) use SED fitting of a single, highly lensed LBG at \( z = 2.7 \) (cB58) to obtain a dust temperature of \( T = 33 \, K \). Although these detections place interesting constraints on the FIR emission from LBGs it is unclear as to whether or not these individual detections are representative of the whole LBG population.

While the typical LBG remains undetected, greater success has been obtained through targeting atypically massive and UV-bright LBGs. Recently, Magdis et al. (2010b) claim a detection in a stacked sample of the most massive LBGs in the Great Observatories Origins Deep Survey-North (GOODS-N) field and obtain a 0.41 mJy flux at 1.1 mm. For any reasonable assumption of dust SED, this suggests that the relatively massive, rest-frame optically selected sources should be detectable at 870 \( \mu m \) at a \( \sim 0.6 \, mJy \) level. At \( z \sim 4 \), Lee et al. (2012) investigated FIR emission from the most actively star-forming systems in the Bootes field \((\sim 2000 \) sources\). They split their sample into three magnitude bins and obtain 350 and 500 \( \mu m \) detections in the two highest luminosity bins – finding that the most UV-luminous systems are the most FIR bright.

However, without multiple direct FIR detections, spanning the peak of the dust emission for the typical source at these redshifts, we can say little about the properties of the obscured material in these systems. Prior to this work the best estimates of the dust SED shape of \( z \sim 3 \) LBGs were either loosely constrained by limits or single wavelength detections (e.g. Magdis et al. 2010c), extrapolated from sub-mm bright sources at similar epochs (e.g. sub-mm galaxies, see discussion in Davies et al. 2012b) or modelled from low-redshift analogous sources (such as blue compact dwarfs (BCDs); Dale et al. 2007). Hence, a direct determination of the dust SED for high-redshift sources is required in order to successfully constrain the dust properties of these systems and investigate their obscured stellar populations.

In our recent study (Davies et al. 2012b), we investigated the FIR emission from a small sample of spectroscopically confirmed \( z \sim 5 \) LBGs. In this new work, we use the Large Apex Bolometer Camera (LABOCA) Survey of the Extended Chandra Deep Field South (LESS) to expand this study and investigate the FIR properties of a large number of both spectroscopically confirmed and photometrically identified LBGs over a range of redshifts. Utilizing the deep 870 \( \mu m \) observations over the relatively large area of the Extended Chandra Deep Field South (ECDF-S), we produce a comprehensive study of FIR emission from high-redshift-unobscured star-forming galaxies. We select sub-samples of the most massive, those predicted to be the most actively star-forming (therefore, potentially the most FIR bright) and most rest-frame UV-bright \( z \sim 3 \) galaxies in the field and obtain detections of the typical source in each sample. We identify two of our samples in the Herschel1 maps of the field at 250, 350 and 500 \( \mu m \) allowing us to constrain the \( z \sim 3 \) LBG dust SED. Therefore, we make the first reliable estimates for the FIR luminosity, obscured star formation, dust mass and dust temperature in these early star-forming systems.

The technical analysis which is undertaken in the paper is comparable to that outlined in Davies et al. (2012b), albeit on a wider range of samples. Hence, we shall only briefly discuss our methods and refer the reader to Davies et al. (2012b) for any further details. We note that, unless otherwise stated, when discussing UV and FIR emission we refer to emission in the rest-frame of the galaxy. Throughout this paper, all optical magnitudes are quoted in the AB system (Oke & Gunn 1983), and the cosmology used is \( H_0 = 70 \, km \, s^{-1} \, Mpc^{-1}, \Omega_m = 0.7 \) and \( \Omega_{\Lambda} = 0.3 \).

2 DATA SETS AND SOURCE SELECTION

The LABOCA (Siringo et al. 2009) is a 295-element bolometer camera mounted on the 12-m Atacama Pathfinder Telescope (APEX) located at Llano de Chajnantor in Chile. It has a bandwidth centre of \( \sim 345 \, GHz \) (870 \( \mu m \)) and half power spectral range of \( \sim 60 \, GHz \). The publicly available LESS map comprises 200 h of integration time, covering the \( 30 \times 30 \, arcmin \)2 of the ECDF-S with a uniform coverage of \( r = 1.2 \, mJy \, beam^{-1} \) and a resolution of 19 arcsec [effective beam full width at half-maximum (FWHM)]. For full details of the LESS survey see Weiß et al. (2009). For our stacking analysis, we shall utilize the LESS residual maps, where the 126 sources of \( >3.7 \sigma \) significance are removed through scaling and subtracting the beam at their positions (see Weiß et al. 2009). We note that we do not stack high-redshift galaxies at the positions of these sub-mm bright sources (see below for details).

The ECDF-S field is extremely well studied, with deep multi-wavelength coverage from X-ray to radio wavelengths. Most notable for this study is the Multi-wavelength Survey by Yale–Chile (MUSYC) survey (Gawiser et al. 2006), which provides deep coverage in 32 (broad and intermediate) bands in the optical and near-IR. Such detailed photometric coverage allows the determination of accurate photometric redshifts over a large redshift range (see Cardamone et al. 2010, for further details).

Initially, we produce a sample of photometrically selected LBGs at \( z \sim 3, 4 \) and 5. We apply colour selection criteria to the deep MUSYC catalogue data in order to identify high-redshift

1 Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.
star-forming galaxies using the Lyman-break technique (e.g. Steidel et al. 1995). These colour selections essentially identify sources with very red colours across the two bluest bands and are aimed at identifying the Lyman break at 1216 Å in the rest frame of the galaxy. We also apply additional cuts to reduce contamination from lower redshift sources (see Stanway et al. 2008). Colour selections at each redshift are given in Table 1. In Fig. 1, we display our colour selection criteria designed to identify high-redshift star-forming galaxies. We overplot the redshift colour evolution of a zero extinction, young, metal-poor high-redshift galaxy produced from the Maraston (2005) stellar population models (red line). Any extinction will push source colours to the upper right of the plot. Hence, our colour selections are designed to include both dust-free and extincted sources. We note that using the MUSYC filters, selecting star-forming galaxies at \( z < 2.8 \) is problematic. Hence, we only include sources \( 2.8 < z < 3.6 \) in our photometrically selected sample at \( z \sim 3 \).

While these selections identify high-redshift star-forming galaxies, they will still be contaminated by low-redshift sources. In order to make our sample more robust we use the Cardamone et al. (2010) catalogue (and references therein) of photometric redshifts in the ECDF-S and only select sources with best-fitting photometric redshift estimates within each redshift range (see Fig. 1). We also remove objects whose 68 per cent confidence (1σ) error range in redshift extends below the lower boundary of our selection redshifts (i.e. lower than 2.8, 3.6 and 4.5, respectively) in order to remove sources which have poorly fit photometric redshifts. Therefore, we essentially treat the 32-band photometric redshifts of the Cardamone et al. (2010) catalogue as a redshift confirmation of our colour-selected sources. We only select sources which both meet our photometric redshift selection and which fall within our colour selection region for high-redshift star-forming galaxies (green points, Fig. 1). The requirement of a robust photometric redshift imposes an \( R = 25.5 \) mag cut on the sample, as photometric redshifts were only derived for objects brighter than this in the earlier work.

In order to expand our samples to ensure robust statistical results, we also select spectroscopically confirmed star-forming galaxies at redshift 2.5–3.6, 3.6–4.5 and 4.7–5.5 using the publicly available redshift surveys in the ECDF-S (Vanzella et al. 2005, 2006, 2008; Popesso et al. 2009). While our photometric sample only extends in redshift down to \( z \sim 2.8 \), we includes spectroscopically confirmed sources down to \( z = 2.5 \) (just 300 Myr later). Had we used the same \( U \)-band filter as that used by Steidel et al. (2003), these objects would have been identified as LBGs (because such a filter has a shorter wavelength red cut-off than that used to select our photometric sample). Given this and the negligible difference in look-back time between \( z = 2.5 \) and \( z = 2.8 \), we are free to include these objects in our lowest redshift sample. Down to \( R = 25.5 \), the magnitude distributions of the photometric and spectroscopic samples are comparable, confirming the spectroscopic sample is a fair representation of the sources selected photometrically.

To constrain this sample to sub-mm faint star-forming galaxies, we then remove galaxies which have (or are spatially close to) sub-mm detections in the LESS map. We define a sub-mm detection as a source which has a \( >3\sigma \) (870 \( \mu \)m) flux in the LESS non-residual map, within 19 arcsec (the LABOCA effective beam) of its optically derived position – a consequence of this is that no source in our sample is individually detected in the LESS map. This process only removes 33 sources from our samples, with 27 in the \( z \sim 3 \) redshift range. By performing a Monte Carlo analysis of our source positions, we find that we would expect \( \sim 20 \) random correlations of \( >3\sigma \) sub-mm bright sources and LBGs at \( z \sim 3 \). Hence, this is consistent with all of these regions being chance superpositions of an LBG and sub-mm source. We also remove any source with a known X-ray counterpart to avoid contamination from high-redshift quasars – which show similar colours to star-forming galaxies.

In addition to our LBGs at \( 2.5 < z < 5.5 \), we also investigate FIR emission from a newly identified sample of spectroscopically confirmed \( z \sim 4.5 \) Lyman \( \alpha \) emitters (LAEs) in the same field (Zheng et al. 2013). No individual LAE was detected in the LESS map.

Our final robust samples of high-redshift star-forming galaxies contain 922, 68 and 20 LBGs at \( z \sim 3, 4 \) and 5, respectively and 46 LAEs at \( z \sim 4.5 \). We note that our \( z \sim 5 \) sample is comparable to that discussed in Stanway et al. (2010) and Davies et al. (2010), and will not provide significantly deeper limits. These sources represent our full high-redshift star-forming galaxies samples. However, the LBG criteria used in the many studies of \( z \gtrsim 3 \) galaxies in the past two decades selects objects based on their unobscured UV emission arising from hot young stars. This inevitably identifies a somewhat heterogeneous sample of sources over a range of stellar mass and dust extinction. A comparatively low-mass source can have the same observed UV properties as a more massive system with a higher extinction and higher overall star formation rate (SFR) (and with a higher FIR luminosity). So while it is valid to explore the FIR properties of sources that are selected using standard LBG criteria, precisely because they represent a type of system that has the basis for a multitude of previous studies of \( z \gtrsim 3 \) galaxies, it is informative to compare these to other samples selected not just as LBGs, but with constraints on their stellar masses and extinction-corrected SFRs. Consequently in this work we derive and explore several sub-samples based on these criteria, restricting these to objects at \( z \sim 3 \) as at this redshift there is sufficient data to make this comparison between the sub-samples and the main LBG sample. We describe each of these sub-samples in the following section.

### 2.1 Sub-samples of the most massive, most actively star-forming and UV-bright rest-frame UV/optical-selected systems at \( z \sim 3 \)

#### 2.1.1 Stellar mass selected sub-samples

Previous work, (e.g. Magdis et al. 2010b), hereafter M10 has indicated that at \( z \sim 3 \) the flux in the observed Spitzer/IRAC bands (rest-frame near-IR) is directly related to the stellar mass of an LBG. In order to select LBGs down to a given stellar mass, we follow M10.

### Table 1. The colour selection criteria used to identify star-forming galaxies at \( z \sim 3, 4 \) and 5. An additional \( I – J \) colour selection is applied at \( z \sim 4 \) and 5 to reduce contamination from low-redshift sources (see Stanway et al. 2008).

| Redshift | Colour | Colour | Colour | Magnitude | IR colour |
|----------|--------|--------|--------|-----------|-----------|
| 2.8–3.6  | \( U – V > 1.2 \) | \( V – R < 1.1 \) | \( U – V > 3.63(V – R) + 0.58 \) | \( V < 26.2 \) | – |
| 3.6–4.5  | \( B – R > 1.6 \) | \( R – I < 1.5 \) | \( B – R > 1.27(R – I) + 1.1 \) | \( R < 27.0 \) | \( I – J < 1.0 \) |
| 4.5–5.5  | \( R – I > 1.5 \) | \( I – z < 1.4 \) | \( R – I > 0.78(I – z) + 1.7 \) | \( 23.0 < I < 25.8 \) | \( I – J < 1.0 \) |
Figure 1. The colour selection of LBGs at $z \sim 3, 4$ and 5 in the ECDF-S. The red line represents the colour evolution of a young, metal-poor source at each redshift produced using the Maraston (2005) stellar population models. All MUSYC sources which meet out magnitude cuts are displayed as black points. Objects which meet our photometric redshift and colour selection criteria are shown as green points (our colour selections are displayed as the grey region bounded by a turquoise dashed line). A small number of sources meet our photometric redshift selection criteria but fall outside of the colour selection window (orange points). Upon inspection of their SED it is unclear as to whether or not these sources are truly high-redshift star-forming galaxies. Hence, they are omitted from any further analysis.

We select one sub-sample with all sources detected at $M < 25.0$ in at least one of the IRAC bands (comparable to the M10 sample – IRAC magnitudes are taken from the Cardamone et al. 2010, catalogue) and a second brighter sub-sample at $M < 22.5$ (10 times more massive assuming a direct relationship between IRAC magnitude and stellar mass). We then also exclude sources which have an X-ray detection in the deep Chandra maps of the field (to rule out bright active galactic nucleus), and once again remove sources which are within 19 arcsec of a >3σ source in the LESS map. Following M10, we use only the spectroscopically confirmed LBGs at $z \sim 3$. The fainter sub-sample (IRAC-25 hereafter) selects almost all the spectroscopically selected LBGs (405 of 425 sources, compared to 51 sources in M10), while the brighter sample (IRAC-22.5) consists of 50 galaxies. All values given in the tables of this paper are for the brighter sample (see Section 4.1 for further details).

M10 use the deep AzTEC 1.1 mm observations of the GOODS-N field to produce a composite image of the positions of their IRAC-detected LBGs. This composite image displays a 0.41 mJy ($\sim 3.7\sigma$)
detection of their sample at 1.1 mm. This suggests that, while typical $z \sim 3$ LBGs remain undetected at sub-mm wavelengths, a stacking analysis of the most massive LBGs should yield a detection. Using our stellar mass selected samples we shall investigate this further. Assuming a dust SED with power-law emissivity, $\beta_{FIR} = 2$, the M10 work predicts an 870 $\mu$m flux of $\sim 0.65$ mJy for a similar sample of IRAC $< 25.0$ $z \sim 3$ LBGs.

While the M10 result may suggest that the most massive $z \sim 3$ LBGs are the most FIR bright (hence, there is a correlation between stellar mass and FIR emission), it is unclear as to whether or not large stellar masses are the prerequisite of observable FIR fluxes. The galaxies in their sample display $z \sim 3.6$ $\mu$m – colours indicative of an old stellar population. In addition, these sources have reasonably large UV luminosities, indicating that they are undergoing a significant burst of unobscured star formation. Hence, either age, unobscured SFR or both may also be a significant factor in determining whether or not an LBG is detectable at FIR wavelengths.

To investigate this further, we also produce two sub-samples of $z \sim 3$ galaxies, one with the largest extinction-corrected SFRs (e.g. Adelberger & Steidel 2000) and another with the largest UV fluxes (representing a typical $z \sim 3$ Lyman-break-selected sample e.g. Steidel et al. 1995).

2.1.2 Extinction-corrected high-SFR sample

In order to select a sub-sample with the largest extinction-corrected SFRs, we apply an extinction correction to the observed rest-frame UV magnitude following the same procedure as that outlined in Adelberger & Steidel (2000). We estimate the UV spectral slope ($\beta_{UV}$) using the best fit to the MUSYC broad and intermediate band observations in the 5000–9000 Å (rest-frame $\sim 1250–2250$ Å) range. We then calculate a rest-frame UV extinction at 1600 Å ($A_{1600\AA}$) using

$$A_{1600\AA} = 4.43 + 1.99 \beta_{UV}. \quad (1)$$

We apply this extinction correction to our spectroscopically confirmed sample, $k$-correct and calculate extinction-corrected SFRs at rest-frame 1600 Å in all sources, using the standard conversion between rest-frame UV flux and SFR (irrespective of $\beta_{UV}$, e.g. Rosa-González, Terlevich & Terlevich 2002):

$$\text{SFR}_\text{UV} (M_\odot \text{yr}^{-1}) = 1.4 \times 10^{-25} L_{\text{UV}} \text{ (erg} \text{s}^{-1} \text{Hz}^{-1}). \quad (2)$$

We then select the top 50, 100, 200 and 250 most highly star-forming sources at $z \sim 3$. We find that the top 200 sources (equating to an extinction-corrected SFR $> 6.7 M_\odot \text{yr}^{-1}$) produces the highest signal to noise in our resultant analysis – hence, we shall only discuss this sample (hereafter the high-pSFR sample). This extinction correction assumes that each galaxy has an intrinsic (unattenuated) $\beta_{UV} \sim -2$ and relies on this premise to predict total SFRs (an intrinsic $\beta_{UV} \sim -2$ model is found to be appropriate for both high-redshift LBGs and local analogues, e.g. Overzier et al. 2011). Therefore, this sample is essentially those sources with the highest predicted SFRs, with the caveat of an assumed $\beta_{UV} = -2$, with any deviation from this slope is caused by dust attenuation. Following the prescription of Meurer, Heckman & Calzetti (1999), this implies that sources with the largest predicted SFRs should display the largest FIR fluxes. Here, we can directly test this prediction by comparing the FIR emission inferred by the assumption that all sources have an intrinsic $\beta_{UV} = -2$, and those directly measured in the FIR. The sample is clearly dominated by those sources with UV spectral slopes that deviate most strongly from $\beta_{UV} = -2$. If, for these sources, the dominant cause of this deviation is not dust extinction, but something else, e.g. variation in stellar population, the sources may be less luminous in the FIR than predicted. As we shall see in Section 6.3, this appears to be the case – suggesting that the unattenuated UV spectral slope is unlikely to be $-2$ (in these sources). Therefore, while we label this sample as ‘high-pSFR’, we note that this is only true by the standards of previous work which have assumed a constant intrinsic UV spectral slope, and later we shall show that this is unlikely to be the case.

2.1.3 UV-brightest sub-sample

The UV-brightest sub-sample, which represents the LBGs with the highest unobscured SFR, is simply a sub-set of our full sample cut at a higher R-band magnitude ($R = 24.43$ rather than $R = 25.5$), the limit chosen to select 200 sources. The choice of sample size is once again assigned retrospectively to achieve the maximum signal to noise in our resultant stacked images (see below), while restricting the sample to the most rest-frame UV-bright sources. This sample contains the UV-bright end (20–25 per cent) of our full LBG selection at $z \sim 3$. The sources are not particularly extreme or rare examples of LBGs; they represent those which are often the subject of spectroscopic studies of $\sim 3$ LBGs (e.g. Shapley et al. 2001).

Using our samples of the most massive (IRAC-25, IRAC-22.5), most actively star-forming (high-pSFR, with the caveats discussed above) and rest-frame UV-brightest (UV-bright) systems, we investigate potential correlations between stellar mass, SFRs and FIR flux at $z \sim 3$. We estimate the mean stellar mass of each sample using the method outlined in Magdis et al. (2010a), which relates IRAC 8.0 $\mu$m magnitude to stellar mass:

$$\log (M_*/M_\odot) = 2.01 - 0.35 M_b, \quad (3)$$

where $M_b$ represents the mean 8.0 $\mu$m magnitude of each sample. The UV-optical properties of all $z \sim 3$ samples are given in Table 2.

3 ANALYSIS

In order to constrain the FIR emission from the average source, data were combined from the positions of all sources in each of our samples. A $30 \times 30$ pixel ($\sim 10 \times 10$ beam size) region centred on each source was extracted from the LESS residual map. These $30 \times 30$ pixel regions were then combined into an average image taking the mean flux at each pixel position over all of the extracted regions (stacking). However, stacking processes involving large-beam deep sub-mm maps which are close to the confusion limit (such as LESS) can be biased by flux arising from both faint and bright nearby sources (see Lutz et al. 2010, for more detailed discussion). First, the number density of faint background sources at the flux level of the LESS map ($\sim 1.2$ mJy) is comparable to the LABOCA beam density. Therefore, there is essentially no blank sky background and all LABOCA beam positions contain flux arising from faint background objects. Secondly, any LABOCA beam position may contain additional flux from the wings of the beam of a nearby bright source. Lutz et al. (2010) perform simple Monte Carlo simulations of model LABOCA data in order to estimate the flux contribution to LESS beam positions from both faint background sources and nearby bright sources. They find that the LESS residual map requires the subtraction of $0.072$ mJy beam$^{-1}$ in order to remove the contribution.
from such sources. Hence, any detection or limit obtained in our stacking analysis must be scaled to reflect this additional flux. Therefore, prior to stacking we subtract 0.072 mJy beam$^{-1}$ from the LESS residual maps, allowing any detected flux in our stacked image to be used directly. However, if no emission is detected in the stacked images, the measured rms will essentially measure fluctuations about this scaling factor. Hence, any further analysis must use a limit of 0.072 (±rms) mJy beam$^{-1}$.

4 RESULTS FOR THE $z \sim 3$ SAMPLES

4.1 The IRAC-25 and IRAC-22.5 samples

Fig. 2 (top left) displays the composite image produced from the IRAC-25 sample. We find that the stacked source is undetected at a ~0.2 mJy (2 × rms) level. This is surprising given the M10 detection in a comparable sample at ~0.4 mJy at 1.1 mm (predicted 0.65 mJy at 870 μm). In order to validate our stacking procedure, we apply our method to a previously published stacked detection in the same field. Greve et al. (2010) use the LESS survey to produce a composite image of ~600 star-forming $BzK$ ($bBzK$) selected galaxies in the ECDF-S, obtaining an ~0.4 mJy detection of the average $bBzK$ in the field. We apply our stacking procedure to an identical sample of $bBzK$ sources in the field and also obtain a ~0.4 mJy detection – thus, suggesting our method is sound. In an additional test, we repeat the procedure outlined in M10. We select their sample of spectroscopically confirmed LBGs in the GOODS-N and apply similar cuts to those described in their work. We then combine the publicly available AzTEC data at their source positions using three independently produced stacking procedures and still do not obtain a detection.

Carrying out the same stacking procedure on the brighter IRAC-22.5 sample (which contains the brightest 12 per cent of the sources in the fainter sample) leads to a 4 × rms detection. The top-right panel of Fig. 2 shows the composite image of this sample displaying a 0.61 ± 0.14 mJy source at the expected position. Clearly if the fainter sample had the same ratio of IRAC to 870 μm flux as the bright sample, we would not have detected it. Furthermore, discussion of stellar mass selected samples is limited to the brighter, IRAC-22.5 sample.

4.1.1 FIR SED of the IRAC-22.5 sample

By carrying out a similar stacking analysis at other wavelengths, we can investigate the SED of the average high stellar mass source.

First, we produce a composite SED of all sources in our IRAC-22.5 sample at optical–NIR wavelengths using the mean magnitudes of our sample in the Cardamone et al. (2010) MUSYC catalogue. Second, we use the deep multiwavelength coverage of the ECDF-S in the MIR and FIR to produce composite images at a number wavelengths covering the dust emission curve at $z \sim 3$. We have used the Far-Infrared Deep Extragalactic Legacy Survey (FIDELS; Dickinson & FIDEL Team 2007) deep Spitzer 24μm maps of the field and stack the positions of our sample – obtaining a ~12σ detection. We then apply a similar procedure to the publicly available Herschel Spectral and Photometric Imaging Receiver (SPIRE) maps of the ECDF-S at 250, 350 and 500 μm taken from the Herschel Multi-tiered Extragalactic Survey (HerMES, Oliver et al. 2012). We remove any contribution from background flux in the Herschel maps by performing a Monte Carlo stacking analysis on random source positions in the field (10 000 realizations) and subtracting the median flux over all realizations. After subtracting this background we obtain a ~4σ detection at 250 and 350 μm, and a tentative 2–3σ detection at 500 μm.

Fig. 3 displays the composite images produced at each wavelength, while Fig. 4 (left) displays the composite SED of the composite IRAC-22.5 source in our sample. We fit a grey body emission curve to our FIR data points, assuming a dust SED with power-law emissivity, $\beta_{\text{FIR}} = 2$, between 20–60 K and find a best-fitting temperature of 39^{+2}_{-3} K. In Fig. 4, we overplot SEDs with fixed temperatures at ±10 K of the best-fitting temperature, displaying that significantly higher or lower temperatures are inconsistent with our data. This represents the first realistic constraint on the dust temperature of non-lensed $z \sim 3$ UV-selected star-forming galaxies.

Following the procedure outlined in Davies et al. (2012b) and references therein, we integrate this grey body over the 8–1000 μm range and infer a typical FIR luminosity of $L_{\text{FIR}} \sim 10^{12}$ L$_{\odot}$ and dust mass of $M_{\text{dust}} \sim 10^{7.5}$ L$_{\odot}$ (all FIR properties of our $z \sim 3$ samples are given in Table 3).

This luminosity is slightly lower than that of all individually detected sub-mm galaxies at $z \gtrsim 3$, which display $L_{\text{SPIRE}} > 10^{12}$ L$_{\odot}$ (Chapman & Casey 2009; Negrello et al. 2010; Conley et al. 2011), but is consistent with $z \sim 1$–2 Submillimeter Galaxies (SMGs) of Banerji et al. (2011), who find $L_{\text{SPIRE}} \sim 10^{10.75}$ L$_{\odot}$. However, the $L_{\text{SPIRE}} \sim 10^{12}$ L$_{\odot}$ sources in Banerji et al. (2011) show significantly lower dust temperatures than those found here (25–30 K) and as such they have larger 870 μm fluxes. While this indicates that the typical SED of our high stellar mass objects is not directly consistent with that of SMGs over a range of epochs, it suggests that massive $z \sim 3$ UV-selected systems may represent sources somewhere between sub-mm bright...
galaxies (with much larger masses) and sub-mm faint typical star-forming galaxies at $z \sim 3$ – displaying significant FIR emission, but being easily detectable in the UV (see Section 6.4 for further discussion). Using the typical IRAC-inferred stellar masses of our IRAC-22.5 sample ($M_* \sim 10^{10.7} M_\odot$), we obtain $M_{\text{dust}} / (M_{\text{dust}} + M_*) \sim 0.0009$, suggesting that only a small fraction of their baryonic content is in the form of dust.

4.2 The high-pSFR sample

We apply a similar stacking procedure using the LESS data to our high-pSFR sample of the 200 spectroscopically confirmed sources with the highest extinction-corrected SFRs. We obtain 0.35 mJy (formally $\sim 4.3 \times \text{rms}$) detection near the central position of the stack (bottom-left panel of Fig. 2), although there is a small (just
FIR emission from high-$z$ galaxies

Figure 3. The composite images produced by stacking the positions of our IRAC-22.5 sample at 24 $\mu$m (left), 250 $\mu$m (middle left), 350 $\mu$m (middle right), 500 $\mu$m (right). Contours display the same significance levels as in Fig. 2 except in the 24 $\mu$m image, where we only display a 10 $\times$ rms level. The typical source is clearly detected ($>4 \times$ rms) at 24, 250 and 350 $\mu$m. We carried out this stacking procedure for each of our sub-samples, but only present the images for the high stellar mass IRAC-22.5 sample here.

Figure 4. The composite SED of our IRAC-22.5 sample (left), high-pSFR sample (middle) and UV-bright sample (right). The black triangles display the mean optical and NIR magnitudes taken from the MUSYC catalogue. The red squares and limits display the values obtained from our stacking analysis in this work. The best-fitting grey body emission curve is plotted as the blue line. For comparison, in the left- and right-hand panels, we overplot SEDs with a fixed best-fitting $\pm$10 K temperature (orange and green lines) – both are found to be inconsistent with the rest-frame FIR data. In the middle panel, we plot the SED with an upper limit to the dust temperature which is still consistent with the data (34K). Properties of these SEDs can be found in Table 3.

Table 3. The FIR properties of our $z \sim 3$ samples.

| Sample       | $S_{870\mu m}$ (mJy beam$^{-1}$) | $\beta_{\text{FIR}}$ | $T_{\text{dust}}$ (K) | $M_{\text{dust}}$ (Log[ML]) | $M_{\text{SFR}}^{\text{FIR}}$ (Log[ML]) | Observed SFR (Log[ML]) | Predicted SFR (Log[ML]) | Observed SFR (per cent) | Predicted $S_{870\mu m}$ (mJy beam$^{-1}$) |
|--------------|----------------------------------|----------------------|-----------------------|-----------------------------|----------------------------------------|------------------------|------------------------|------------------------|----------------------------------|
| IRAC-22.5    | 0.62 $\pm$ 0.14                  | 2.0                  | 39$^{+2}$            | 12.0                        | 7.7$^{+0.2}$                          | 168$^{+84}$            | 83$^{+5}$              | 83$^{+5}$              | 0.68$^{+0.24}$                          |
| High-pSFR    | 0.35 $\pm$ 0.08                  | 2.0                  | <34$^{+2}$          | 11.5                        | >7.5                                  | <56                    | >2.8                   | >2.8                   | <68$^{+13}$                               |
| UV bright    | 0.37 $\pm$ 0.09                  | 2.0                  | <34$^{+2}$          | 11.5                        | >7.5                                  | <56                    | >2.8                   | >2.8                   | <68$^{+13}$                               |
| All $z \sim 3$ | <0.09                           | 2.0                  | 35$^{+1}$           | <10.9                       | <7.0                                  | <16                    | >2.6                   | >2.6                   | <68$^{+13}$                               |

Properties derived from the best-fitting SED dust temperature. *The ratio of observed to UV-predicted FIR SFRs. ^Predicted 870 $\mu$m flux, assuming the UV-predicted obscured SFR given in Table 2 and best-fitting SED dust temperature. As we have no detections with which to constrain the dust temperature of our full sample, it is assumed to be 35 K.
Figure 5. Composite 870 µm images of the positions of our full samples of high-redshift star-forming galaxies in the ECDF-S at \( z \sim 3 \) (top left), 4 (top right), 4.5 (bottom left) and 5 (bottom right) convolved with a Gaussian of the same FWHM as the LABOCA beam size. Contours show both positive (green) and negative (red) deviations of 2 (dotted line) and 3 (dashed line) \( \times \) rms away from the mean value in the field. The LABOCA beam size is displayed as the black circle.

4.3 The full and UV-bright sample

These two samples represent a standard LBG selection typical of many previous studies of \( z \sim 3 \) LBGs, and a higher unobscured UV-luminosity cut of the same sample. The latter contains a mix of sources with either more ongoing star formation, or less extinction towards their star-forming regions than the former. We apply our 870 µm stacking procedure to both samples and find no detection for the full sample (to a limit of \(< 0.09 \) mJy). A similar stacking of the Herschel SPIRE data for these sources again results in non-detections. The properties of this sample are summarized in Tables 2 and 3, assuming, in the absence of any detection in the FIR a dust temperature of 35K, and the image of the 870 µm stack is shown along with those of the full samples at higher redshift in Fig. 5.

Stacking the 870 µm data for the UV-bright sample of the 200 \( R \)-band brightest \( z \sim 3 \) LBGs, we obtain an average flux of 0.37 mJy (\( \sim 4 \times \) rms, bottom-right panel of Fig. 2). We note again that there is an overlap between our IRAC-22.5 and UV-bright samples (20 sources). If we remove these sources we still obtain a detection once again at a slightly lower signal to noise, but still consistent with Poisson statistics. The measured flux density in our UV-bright sample is almost identical to that obtained for the high-pSFR sample. The typical stellar mass of UV-bright sample is \( M_\star \sim 10^{10.35} M_\odot \) – also similar to the high-pSFR sample. In fact, the only significant difference between our high-pSFR and UV-bright samples is their UV spectral slopes (\( \beta_{\text{UV}} = -1.4 \) and \( \beta_{\text{UV}} = -1.8 \), respectively, with mean spectral slope error on an individual source of \( \sim \pm 0.06 \) ).
almost identical 870 µm flux is surprising given that the UV spectral slope is thought to be indicative of extinction, with the extinted flux re-emitted in the FIR (e.g. Meurer et al. 1999; Adelberger & Steidel 2000; Finkelstein et al. 2009). The lack of variation of observed 870 µm flux with these samples, potentially suggests a lack of correlation between UV spectral slope and FIR emission (at least for sources with the largest deviation from \( \beta_{UV} = -2 \)) and that the actual total SFR in our supposed high-pSFR sample is no higher than for our UV-bright sample. This will be discussed further in Section 6.3.

We once again consider these sources in both the Herschel SPIRE maps and Spitzer MIPS maps of the field. Fig. 4 (right) displays the composite SED of our UV-bright sample. We fit a grey body emission curve to our FIR data points, assuming a dust SED with power-law emissivity \( \beta_{FIR} = 2 \), and find a best-fitting temperature of 34 ± 1 K. We note that this temperature is consistent with that used in our previous study of \( z \approx 5 \) sources (Davies et al. 2012b), strengthening the validity of that analysis. We over plot SEDs with fixed temperature at 24 and 44 K, once again displaying that significantly higher or lower temperatures are inconsistent with our data. At 34 K, we infer an FIR luminosity of \( L_{FIR} \sim 10^{11.5} \text{L}_\odot \) and dust mass of \( M_{dust} \sim 10^{6} \text{M}_\odot \) for the composite source in our UV-bright sample. Using the IRAC-inferred stellar masses, we obtain \( M_{dust}/M_{dust} + M_s \sim 0.0017 \) consistent with the high-pSFR sample and the high stellar mass IRCAC-22.5 sample.

5 RESULTS FOR HIGHER REDSHIFT LBGs

At higher redshifts LBGs are likely to display much lower FIR fluxes, assuming the same SED shape as our detected \( z \sim 3 \) samples — while the increasing luminosity distance and inverse K-correction provide roughly equal and opposite scaling to the observed flux at higher redshifts, LBGs at \( z \gtrsim 3 \) are significantly less massive than those at \( z \sim 3 \) (Verma et al. 2007). Therefore, are likely to be less FIR luminous assuming the potential \( L_{FIR} \)—stellar mass correlation discussed previously. Coupled with the smaller sample sizes, it is unlikely that the typical \( z > 3 \) LBG will be detected in our composite images.

Fig. 5 displays the stacked images produced from our complete LBG samples at \( z \sim 3 \) (discussed above), \( z \approx 4 \) and 5, and the LAE sample at \( z \approx 4.5 \). We find that no source is detected at a \( \gtrsim 2 \times \text{rms} \) level in the centre of any of the composite images. We do obtain an \( \sim 2 \sigma \) detection close to the central region in our \( z \sim 5 \) sample. However, this is consistent with the noise characteristics of the data. Table 4 displays the properties of the composite source at each redshift, derived from our stacked images. These non-detections are consistent with our dust1998). SED shape for the UV-bright sample (which is likely to be most appropriate at \( z > 3 \)) being applicable to LBGs at \( z > 3 \), only scaled in UV luminosity and stellar mass.

As the typical LBGs remains undetected in our composite images at all epochs, we note that observations much deeper than those previously obtained are required to individually detect these systems (reaching \(<0.2 \text{mJy})\). Observations such as these are impractical with single dish observatories and therefore with require observations with high sensitivity interferometers—e.g. the fully operational Atacama Large Millimeter/Submillimeter Array (ALMA).

In combination, our results suggest that high-redshift LBGs galaxies have low dust content (<0.1 per cent of their total baryonic mass). This result, coupled with the lack of large quantities of molecular gas in these systems (Livermore et al. 2012; Magdis et al. 2012), suggests that they do not have large quantities of baryonic material which is not observable in the rest-frame UV. This has important consequences for the nature of the LBG phenomenon, suggesting that they are independent starburst galaxies with little obscured material and not low extinction sight-lines through a much larger obscured system (see Davies et al. 2010, 2012b, for discussion).

6 DISCUSSION

6.1 Comparisons to other populations

As the detections at \( z \sim 3 \) represent some of the first multi-frequency constraints to the dust SED of the population of unlensed LBGs, it is interesting to consider the FIR properties of these sources in comparison to other populations of galaxies. The most direct comparison can be made with the recent detection of FIR emission from LBGs at \( z \sim 4 \). As noted previously, Lee et al. (2012) stacked the Herschel SPIRE data at the positions of \( z \sim 4 \) LBGs in the Bootes field. They obtain a detection of the rest-frame UV-brightest sources at 350 and 500 µm. Their detected sample consists of sources with \( I_{AB} < 24.3 \), hence is roughly equivalent to the R-band magnitude limits of our UV-bright sample (both represent an observation of the rest-frame UV continuum at their respective redshifts). Their FIR fluxes are 1–2 mJy and have best-fitting SEDs with dust emission peaking at \( \gtrsim 100 \) µm in the rest frame of the galaxy. Our results on the \( z \sim 3 \) LBGs are consistent with these, assuming that there is no evolution in the physical properties of galaxies selected to have similar rest-UV properties, with the dust SED of our UV-bright sample reaching a maximum of 2.1 ± 0.58 mJy and potentially rising in emission out to 500 µm.

It is also interesting to consider whether or not these systems display similar dust/stellar mass characteristics to those selected for their high sub-mm luminosity, and whether they could potentially

| Redshift | Sources\(^a\) | \( N_{gal} \) | \( S_{70} \) (mJy beam\(^{-1}\)) | \( \beta_{FIR} \) | \( T_{dust} \) (K) | \( L_{FIR} \) (Log[\text{L}_\odot]) | \( M_{dust} \) (Log[\text{M}_\odot]) | \( M_{dust}/M_s \) | SFR\(^b\) (M\(_\odot\) yr\(^{-1}\)) |
|----------|----------------|----------|----------------|-------------|-------------|----------------|----------------|----------------|----------------|
| 3.6–4.5  | V-drops        | 68       | 0.35           | 2.0         | 35          | \(<11.5\)         | \(<7.1\)         | \(<0.006\)     | \(<56\)         |
| 4.5      | LAEs           | 46       | 0.40           | 2.0         | 35          | \(<11.6\)         | \(<7.1\)         | \(<0.112\)     | \(<62\)         |
| 4.7–5.5  | R-drops        | 20       | 0.61           | 2.0         | 35          | \(<11.7\)         | \(<7.3\)         | \(<0.012\)     | \(<92\)         |

\(^a\)Source types: V-drops and R-drops: LBGs samples at \( z \sim 4 \) and 5 selected in this study and LAEs: Lyman \( \alpha \) Emitters at \( z \sim 4.5 \) identified in Zheng et al. (2013). \(^b\)2 × \text{rms} limits including the 0.072 mJy beam\(^{-1}\) scaling factor used to account for source confusion. \(^c\)FIR Luminosity limit derived for our 2 × \text{rms} (+0.072 mJy beam\(^{-1}\)) limit. \(^d\)Dust mass at a 2 × \text{rms} (+0.072 mJy beam\(^{-1}\)) limit. \(^e\)The cool dust to stellar mass fraction. Stellar masses are taken as the mean mass of a typical source at \( z \approx 4 \) (\( \sim 10^{8.3} \text{M}_\odot \), Hathi et al, in preparation), \( z \sim 4.5 \) (LAEs \( \sim 10^{6.9} \text{M}_\odot \), Finkelstein et al. 2007) and \( z \approx 5 \) (\( \sim 10^{9.2} \text{M}_\odot \), Verma et al. 2007). \(^f\)The obscured SFR derived using the Kennicutt relation (Kennicutt 1988)
evolve into such systems at a later epoch. Fig. 6 shows the stellar mass against dust mass for our detected sub-samples. We also show the properties of low-redshift sources from the Herschel KINGFISH survey (Skibba et al. 2011) and Herschel Virgo cluster survey (Davies et al. 2012a; Auld et al. 2013), z > 2.5 sub-mm sources (Michałowski, Hjorth & Watson 2010) and metal-poor BCD galaxies (Hunt et al. 2005). Our samples fall very close to the linear best fit to the data and are consistent with, but at the high-mass end, of the low-redshift systems. While they fall far below the SMGs both in dust and stellar mass, they do display similar dust fractions. Interestingly, our LBGs display significantly lower dust to stellar mass fractions than those found for the local BCDs. Although significantly less massive, these BCDs have specific SFRs and metallicities which are similar to LBGs and have been proposed as scaled down LBG analogues at low redshift. The difference in $M_{\text{dust}}/M_*$ ratio between these sources and our LBG samples suggests that care must be taken in comparing BCDs with LBGs, as they may display distinctly different dust characteristics. We note that the most well studied low-redshift LBG analogue (Haro II, see Heckman et al. 2005; Galametz et al. 2009, etc) displays an almost identical stellar to dust mass ratio to our sub-samples – suggesting that Haro 11 may have similar dust properties to $z \sim 3$ LBGs. However, Galametz et al. (2009) find a dust SED for Haro 11 peaking at $\sim 40 \mu$m in the rest frame. This corresponds to a dust SED peaking at 160 $\mu$m for an identical source as $z \sim 3$ and is inconsistent with our LBG samples – it would require a dust SED which peaks below our Herschel 250 $\mu$m point, which is unlikely given the rising flux in both our SEDs between 250 and 350 $\mu$m. This suggests that Haro 11 displays a much higher dust temperature than our $z \sim 3$ LBGs. This is intriguing given that Haro 11 shares many other characteristics with LBGs at $z \sim 3$ and may potentially display differences between the interstellar medium topography in Haro 11 and our high-redshift sources.

Recently a number of studies have investigated the molecular gas content of LBGs (e.g. Livermore et al. 2012; Magdis et al. 2012) finding that, consistently over a number of sources, the molecular gas content of LBGs is roughly the same as their stellar mass (i.e. the stellar and molecular gas content each make up $\sim 50$ per cent of the total baryonic mass). Assuming a similar molecular gas fraction in our systems, and the same stellar to dust mass scaling, we predict their potential growth through star formation (irrespective of merging). The red arrows in Fig. 6 display the maximum growth of the systems assuming 100 per cent efficiency in the conversion from molecular gas to stars, no accretion of cool gas on to the galactic halo from filaments in the large-scale structure, and evolution with the same $M_{\text{dust}}/M_*$ ratio (i.e. following the same slope as the observed linear correlation for low-redshift sources). We find that at best these systems will reach $\sim 10^{11} M_\odot$, and exhaust all of their molecular gas in $\lesssim 500$ Myr. Therefore, despite displaying FIR fluxes, it is unfeasible that these systems will grow into sub-mm bright galaxies through the conversion of all of the available material into stars – they would require a significant number of major mergers to reach the required mass. However, this does not rule out our samples (specifically the IRAC-22.5 sample) representing the very low mass end of the sub-mm galaxy distribution, which falls below the individual source detection limit of sub-mm observatories (see Section 6.4).

Lastly in this section, we consider the dust temperature of our composite sources – $39_{-3}^{+2}$ K for the high stellar mass IRAC-22.5 sample, $<34$ K for the high-pSFR sample and $34_{-3}^{+1}$ K for the UV-bright sample. Lee et al. (2012) estimate dust temperatures of $\sim 30$ K for $z \sim 4$ LBGs, although they only obtain detections shortward of the dust peak and hence cannot accurately constrain the temperature. We note that our dust peak position is largely constrained by our 870 $\mu$m detection – producing a best-fitting SED to higher temperatures than the Lee et al. (2012) result (for reasonable assumptions of power-law emissivity). Reddy et al. (2012) also obtain a best-fitting temperature of $\sim 30$ K for systems at $z \sim 2$, although they also do not have a detection longward of the dust peak. More generally, if we once again compare our composite sources with other galaxy populations, we find that our dust temperatures are more consistent with the sub-mm bright sources (mean $\sim 41$ K, Michałowski et al. 2010) and ‘power-law’ SED-type distant obscured galaxies at $z \sim 2$ (median $\sim 35$ K; Melbourne et al. 2012) than with $z \sim 1$–2 SMGs (25–30 K, Banerji et al. 2011) and local galaxies – mean $\sim 27$ K (Skibba et al. 2011, although calculated for a $\beta_{\text{FIR}} = 1.5$ model, they state that assuming $\beta_{\text{FIR}} = 2.0$ only produces slightly lower temperatures) and $\sim 20$ K (Davies et al. 2012a; Auld et al. 2013).

In summary, we find that our comparatively high stellar mass IRAC-22.5 sample shares many characteristics with sub-mm bright sources at the same redshift, albeit at much lower masses. They have similar stellar to dust mass ratios and dust temperatures. These systems may therefore represent the low-mass end of the sub-mm galaxy distribution (see Section 6.4). Our other sub-samples appear to have lower dust temperatures, more consistent with previous.
estimates for typical star-forming galaxies at $2 < z < 4$, but higher than $z \sim 1$–2 SMGs and local galaxies.

6.2 Total SFRs and the ‘main sequence’ of star-forming galaxies

These results provide a direct measurement of these systems’ FIR luminosity, and hence obscured SFR. Previous studies have attempted to constrain total SFR (obscured + unobscured) in high-redshift galaxies by correcting unobscured SFRs – applying a reddening model to the observed UV-optical emission (e.g. Magdis et al. 2010a). Here, we provide a more direct measurement of the obscured star formation, allowing us to constrain the total SFR in our samples of $z \sim 3$ systems.

We use our integrated $L_{\text{FIR}}$ to obtain an FIR-derived SFR limit, using the Kennicutt relation for local starburst galaxies (Kennicutt 1998):

$$SFR_{\text{FIR}} \left( M_\odot \text{yr}^{-1} \right) = 4.5 \times 10^{-44} L_{\text{FIR}} \text{ (erg sec}^{-1} \text{)},$$

(4)

We derive a typical obscured SFR for our stellar mass selected IRAC-22.5 sample $\sim 170 M_\odot \text{yr}^{-1}$ (see Table 3). If we once again use the conversion between UV flux and SFR (equation 2), we obtain a typical unobscured SFR of $\sim 34 M_\odot \text{yr}^{-1}$, hence a total SFR of $\sim 200 M_\odot \text{yr}^{-1}$. Applying the same procedure to the high-pSFR and UV-bright samples, we obtain a total SFR of $<80 M_\odot \text{yr}^{-1}$ and $\sim 85 M_\odot \text{yr}^{-1}$ (see Tables 2 and 3 for individual breakdown). For at least the UV-bright and the IRAC-22.5 samples the majority (up to $\sim 80$ per cent) of the star formation is obscured. As noted earlier, the behaviour of the sample selected to have the highest SFR (assuming the slope of the UV SED reflects significant extinction and we can accurately characterize that extinction) is unexpected. For any reasonable dust temperature, it appears to have a lower total SFR to both the UV-bright and stellar mass selected samples. We discuss this further in Section 6.3.

Using our IRAC-inferred stellar masses and total SFRs, we can consider our samples in comparison to the ‘main sequence’ of star-forming galaxies. A number of recent studies (e.g. Elbaz et al. 2007; Noeske et al. 2007; Daddi et al. 2008; Magdis et al. 2010a; Rodighiero et al. 2010) have displayed a correlation between UV-corrected (total) SFRs and stellar mass in star-forming galaxies out to $z \sim 3$. This ‘main sequence’ of star-forming galaxies, predicts increasing star formation activity with stellar mass (as found in our results). Magdis et al. (2010a) determine this relation for a sample of IRAC detected LBGs $z \sim 3$ (see their fig. 7). Fig. 7 displays the SFR as a function of stellar mass for star-forming galaxies at a range of redshift. We find that our samples are consistent with the Magdis et al. (2010a) relation, falling close to their best-fitting correlation and displaying a similar slope of increasing star-formation activity with stellar mass. We estimate potential errors on the obscured SFR induced by our SED fitting by calculating $L_{\text{FIR}}$ (and therefore SFRs) for the range of dust SED temperatures consistent with our data. We find at most 50 per cent error in our obscured SFRs. These samples are also consistent with the correlation obtained for $sBzK$ at $z \sim 2$ Daddi et al. (2008), unsurprising as they have similar characteristics to those of the more massive $z \sim 3$ LBGs. We also plot a range of potential SFRs for our full $z \sim 3$ sample. The upper limit of this is constrained by the observed UV SFR + the limit to the obscured SFR derived from our stacked image. The lower limit is constrained by the observed UV SFR alone. We find that our full $z \sim 3$ sample falls below the best fit to the $z = 3$ main sequence, but is still consistent with the spread of source properties in Magdis et al. (2010a). Clearly with only four data points we cannot constrain the SFR–stellar mass relation further. However, it is interesting to note that using a more direct measurement for the total star formation (UV+FIR) in $z \sim 3$ systems, as discussed here, is consistent with the previously obtained correlation. We once again plot the measurement for local LBG analogue Haro 11 (green square, SFR $\sim 25 M_\odot \text{yr}^{-1}$; Grimes et al. 2007) and find a lower SFR/$M_\odot$ ratio than our detected $z \sim 3$ sub-samples. However, Haro 11 is still consistent with our full $z \sim 3$ sample and the main sequence of star-forming galaxies at $z \sim 3$ (Magdis et al. 2010a).

6.3 Testing previous UV continuum slope predictions

In a number of previous studies it has been suggested that deviations from the intrinsic UV continuum spectral slope ($\beta_{\text{int}}$) can be used to predict the FIR emission from high-redshift sources (e.g. Meurer et al. 1997; Chapman et al. 2000; Chapman & Casey 2009; Finkelstein et al. 2009). The presence of dust will preferentially attenuate shorter wavelength photons causing the UV spectral slope to be reddened. This attenuated flux will be re-emitted at FIR wavelengths. Hence, there ought to be a correlation between the quantity of flux
absorbed in the UV, and that which is emitted in the FIR. However, such an analysis relies on the premise that all deviation from a UV spectral which is relatively flat in $f_\beta$ ($\beta_{\text{UV}} \sim -2.0$ for a Salpeter IMF) is caused by dust extinction rather than being intrinsic to the source’s stellar populations and requires that we know the form of the dust extinction. Here, we can directly test the reliability of these predictions by comparing the rest-frame UV and FIR characteristics of our sub-mm detected samples. Similar analysis has previously been undertaken with FIR observations of lensed $z \sim 3$ LBGs and exceptionally FIR bright Lyman-break-selected sources (see summary in Chapman & Casey 2009). These studies find mixed results, with lensed LBGs displaying FIR fluxes which are roughly consistent with the UV spectral slope predictions (within a factor of $\sim 2$) and FIR bright LBGs being under predicted by up to a factor of $\sim 6$ (WestDMMD11, Chapman & Casey 2009). In addition to these, two LBGs (the Cosmic Eye and Cosmic Horseshoe) have had their FIR emission inferred from CO observations (Greve et al. 2005) and in both cases the CO inferred FIR emission is below the UV-predicted value.

For our $z \sim 3$ samples, we calculate UV-predicted SFRs in a similar manner to that discussed in Section 2.1 for the high-pSFR sample. We calculate the UV spectral slope ($\beta_{\text{UV}}$) in the rest-frame $1250 - 2250$ Å and estimate the total extinction-corrected SFR for each of our $z \sim 3$ galaxies as in Section 2.1. We then subtract the observed unobscured UV SFR from the total SFR to obtain a predicted FIR SFR (assuming all flux absorbed in the UV is re-emitted at FIR wavelengths). We use this SFR to calculate a predicted FIR luminosity and, for the best-fitting temperature in our SED fitting, calculate a predicted 870 µm flux (see Tables 2 and 3). Fig. 8 shows the observed against predicted FIR fluxes for our $z \sim 3$ sub-samples (red points). We overplot the values obtained for lensed LBG (green diamonds), FIR bright LBGs (black stars) and LBGs with FIR fluxes estimated from CO measurements (orange diamonds) – all taken from the summary table in Chapman & Casey (2009). The dashed line displays a 1:1 correlation. We find the observed fluxes from our IRAC-22.5 and UV-bright samples are consistent with the UV-continuum slope predictions and the limit from our full $z \sim 3$ sample is consistent with being within a factor of 2 UV-predicted values – similar to the lensed sources, suggesting that the these highly magnified, serendipitous source may be representative of the general population (note that the range of UV-predicted fluxes for the full sample represents a temperature range from 30–40 K). However, in our high-pSFR sample the UV prediction overestimates the observed FIR flux by at least a factor of $\sim 3$ indicating that at least one of the assumptions used in predicting the total SFR (the intrinsic UV slope, form of the dust correction) is likely to be incorrect for this sample.

Interestingly, we find that our high-pSFR and UV-bright samples have distinctly different predicted FIR fluxes, while their observed fluxes are comparable. These samples are almost identical in mean rest-frame UV (1600 Å) magnitude, suggesting that they share similar unobscured SFRs, and have comparable stellar masses, but display significantly different UV spectral slopes ($\beta_{\text{UV}} = -1.44$ and $\beta_{\text{UV}} = -1.76$, respectively, as noted previously). Following the previously suggested scenario, this shallower spectral slope should be indicative of greater FIR emission (for the same UV magnitude, as is the case here). While the dust temperature of the high-pSFR sample is not well constrained, the non-detections in the Herschel bands predict an upper limit to the temperature of $\sim 34$ K. Extrapolating further, to obtain an SFR which is consistent with that predicted from the UV-continuum slope, we would require a dust temperature of $\sim 42$ K. This is clearly ruled out by the Herschel non-detections.

With the caveat that these values are constrained from the mean of a large sample (and hence will not show source to source variation), this result suggests that potentially the FIR emission from these sources is not directly correlated to the UV spectral slope, and may be dependent on other factors – thereby implying that an assumption that all sources have an intrinsic spectral slope of $\beta_{\text{UV}} = -2.0$ may be invalid, or that the assumptions in correcting for dust extinction are incorrect. Following this our high-pSFR sample is not in fact a sample of the moderately star-forming LBGs when we consider the FIR emission directly.

The failure of the dust correction to predict the FIR luminosity of the high-pSFR sample does not necessarily indicate that the correction procedure is inappropriate for most objects (it appears appropriate for the IRAS-22.5 and UV-bright samples). The method of selection for the high-pSFR sample means it contains objects with the largest UV-slope correction, while at the same time having relatively high observed UV fluxes – resulting in the largest correction for obscured star formation. It is possible this combination of properties may indicate that the sources have red UV slopes for reason other than dust attenuation (possibly a wide range of ages, star-formation histories or both). Clearly, there are $z \sim 3$ objects with higher SFRs than the rest of our samples (such as typical SMGs), but these objects may be so reddened that they miss our V-band or $V - R$ cuts and therefore are not selected by us.
6.4 Correlations with stellar mass–low-mass SMG-type sources

Our results imply a correlation between stellar mass and FIR emission. While this is similar to the ‘main sequence’ of star-forming galaxies, it does not contain any correlation of stellar mass with UV emission and simply relates the stellar mass to the observed FIR emission directly. Fig. 9 (inset) displays observed FIR flux against stellar mass for our $z \sim 3$ samples. We find a decreasing 870 $\mu$m flux with decreasing stellar mass between our four samples, indicating that irrespective of UV spectral slope and UV SFRs, more massive systems have larger FIR fluxes. Additionally, in the full Fig. 9, we compare our samples with the distribution of $z > 2.5$ sub-mm galaxies taken from (Michałowski et al. 2010), with fluxes scaled to a flux assuming the source is at $z = 3$. We also over plot the predicted correlation derived from hydrodynamical simulations of isolated disc galaxies at $z \sim 3$ (which may be appropriate for both SMGs and LBGs – blue dashed line, Hayward et al. 2013). We find that this model overpredicts the 870 $\mu$m flux from all of our samples, potentially due to the fact that Hayward et al. models assume that the galaxy is completely obscured (this will not be the case for our rest-frame optically selected galaxies). However, our samples are consistent with this model when considering the scatter in the SMG population.

A simple interpretation of this is that the most massive LBGs at $z \sim 3$ are simply the low-mass end of the sub-mm mass function at $z \sim 3$. This is consistent with the assertion of Michałowski et al. (2012), that SMGs are not pathological objects but the top end of the ‘typical’ galaxy mass function at high redshifts. We have essentially highlighted a sample of more ‘typical’ $z \sim 3$ galaxies (than SMGs) and shown their FIR characteristics to be an extension of those found in sub-mm luminous sources, albeit at lower masses. Our populations display number densities of $\sim$ few $\times 10^{-3}$ Mpc$^{-3}$ for our full $z \sim 3$ sample, $\sim$ few $\times 10^{-4}$ Mpc$^{-3}$ for the UV-bright sample and $\sim 10^{-5}$ Mpc$^{-3}$ for the stellar mass selected IRAC-22.5 sample. These are significantly higher than those derived for $z \sim 2.5$ spectroscopically confirmed SMGs (Chapman et al. 2005), but are fully consistent with an extension of the lower luminosity end of the $z \sim 2.5$ FIR luminosity function (Fig. 10).

This adds weight to the argument of a continuous ‘main sequence’ of star-forming galaxies at high redshift, with simply the fraction of obscured star-formation increasing with stellar mass – starting with mostly unobscured ‘typical’ LBGs, through the massive IRAC-22.5 LBGs of our sample, to SMGs. Clearly, identifying systems in the main sequence ‘void’ between LBGs and SMGs (around $M_* \sim 10^{11} M_\odot$) will be problematic. As systems become more extincted, they will be less UV luminous and drop out of Lyman-break-selected samples. However, these galaxies may not be FIR luminous enough to be identified in deep sub-mm surveys. Fig. 9 suggests that we may hope to identify a sample of yet more massive ($\sim 10^{11}$ $M_\odot$) $z \sim 3$ galaxies with FIR fluxes in the 1.0–3.0 mJy range. Such systems would potentially populate the ‘main sequence’ between SMGs and LBGs, displaying both significant unobscured and obscured star-formation, with the fraction of obscured material increasing with stellar mass. Key targets for the identification of such sources will be the most massive systems at $z \sim 3$, which nonetheless fail to reach the detection limits in current deep sub-mm surveys.

7 SUMMARY AND CONCLUSIONS

We have selected robust samples of LBGs over a range of epochs in the ECDF-S selecting 922, 68 and 20 LBGs at $z \sim 3$, 4 and 5, respectively. We produce composite images of these full
samples at 870 µm and do not obtain detections. At z ≈ 3, where our sample size allows, we selected sub-samples of LBGs on stellar mass, predicted (extinction corrected) total SFRs and UV luminosity. We produce composite images of these sub-samples at multiple wavelengths spanning the dust emission peak at z ≈ 3 and constrain the dust SED of our stellar mass and UV-selected samples. Using this we calculate best-fitting dust temperatures (33–41 K), FIR luminosities (10^{11.5–12.0} L⊙) and obscured SFRs (≈40–250 M⊙ yr⁻¹ including errors), and find that a significant fraction of their star formation is obscured – up to 80 per cent. We compare the FIR properties of our samples with other galaxy populations and find that our stellar mass selected sample shares some characteristics with SMGs at the same epoch, albeit at lower masses and FIR luminosities – they have similar dust fractions and temperatures (≈40 K). We calculate total (UV+FIR) SFRs for our samples and find that they all fall on the main sequence of star-forming galaxies at high redshift, suggesting that direct measurements of the obscured SFRs in these systems leads to total SFRs which are consistent with previous predictions (which do not use detections in the FIR).

A number of these previous predictions use the UV-continuum slope, β_{UV}, to estimate FIR fluxes from high-redshift sources – essentially assuming any deviation from an intrinsic spectral slope of −2 is due to dust attenuation. Here we test those predictions directly by comparing the UV slope inferred 870 µm emission with that observed directly in our composite images. We find that for our full z ≈ 3 sample, stellar mass selected sample and UV-bright sample, the predictions match the true FIR emission relatively well (within a factor of 2). However, for those LBGs predicted to have the highest total SFR, generally those bright in the UV but with the largest deviation from a flat (β = −2)UV spectral slope, this correction does not appear to work. The true 870 µm flux of these sources is similar to samples with the same observed UV luminosity, but with flatter UV spectral slopes and a factor of ~3 times lower than predicted. This does not indicate that this method is inappropriate for the majority of sources, just those with the most extreme corrections. It appears that the most highly star-forming systems (with rates of several 100 M⊙ yr⁻¹) do not appear in our sample, presumably as they fail to make our LBG magnitude and/or colour cuts due to their reddening.

We predict rest-frame optically derived stellar masses for our samples and display a potential correlation between stellar mass and 870 µm flux (consistent with the non-detections in our full samples at all redshifts). The most simple interpretation of this is that our sub-mm detected samples are simply the low-mass end of the sub-mm mass function at z ≈ 3. We also compare the number density of our samples to those for SMGs at z ≈ 2.5 and show that our sample may well represent the lower luminosity end of the high-redshift FIR luminosity function. Assuming this stellar mass to FIR flux correlation extends to lower masses, and the same dust SED is applicable in higher redshift systems, observations much deeper than those obtainable by single dish observatories will be required to individually detect the typical LBG at z > 3.

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