The SCUBA-2 Cosmology Legacy Survey: the nature of bright submm galaxies from 2 deg$^2$ of 850-µm imaging

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ABSTRACT

We present physical properties [redshifts ($z$), star formation rates (SFRs) and stellar masses ($M_{\text{star}}$)] of bright ($S_{850} \geq 4$ mJy) submm galaxies in the $\simeq 2$ deg$^2$ COSMOS and UDS fields selected with SCUBA-2/JCMT. We complete the galaxy identification process for all ($\simeq 2000$) S/N $\geq 3.5$ 850-µm sources, but focus our scientific analysis on a high-quality subsample of 651 S/N $\geq 4$ sources with complete multiwavelength coverage including 1.1-mm imaging. We check the reliability of our identifications, and the robustness of the SCUBA-2 fluxes by revisiting the recent ALMA follow-up of 29 sources in our sample. Considering $> 4$ mJy ALMA sources, our identification method has a completeness of $\simeq 86$ per cent with a reliability of $\simeq 92$ per cent, and only $\simeq 15$–20 per cent of sources are significantly affected by multiplicity (when a secondary component contributes $> 1/3$ of the primary source flux). The impact of source blending on the 850-µm source counts as determined with SCUBA-2 is modest; scaling the single-dish fluxes by $\simeq 0.9$ reproduces the ALMA source counts. For our final SCUBA-2 sample, we find median $z = 2.40^{+0.10}_{-0.04}$, SFR = $287 \pm 6 M_\odot$ yr$^{-1}$ and log($M_{\text{star}}/M_\odot$) = $11.12 \pm 0.02$ (the latter for 349/651 sources with optical identifications). These properties clearly locate bright submm galaxies on the high-mass end of the ‘main sequence’ of star-forming galaxies out to $z \simeq 6$, suggesting that major mergers are not a dominant driver of the high-redshift submm-selected population. Their number densities are also consistent with the evolving galaxy stellar mass function. Hence, the submm galaxy population is as expected, albeit reproducing the evolution of the main sequence of star-forming galaxies remains a challenge for theoretical models/simulations.

Key words: dust, extinction – galaxies: evolution – galaxies: high-redshift – galaxies: star formation – galaxies: stellar content – submillimetre: galaxies.

1 INTRODUCTION

Since their discovery almost twenty years ago [Smail et al. 1997; Hughes et al. 1998; Barger et al. 1998], the nature of galaxies selected at submillimetre (submm) wave-
lengths (submm galaxies), and their role in galaxy evolution has been the subject of extensive study (see Casey, Narayanan, & Cooray 2014 and Blain et al. 2002 for reviews). Of particular importance is the determination of the mechanism that drives the huge star formation rates (SFRs), and hence huge far-infrared luminosities) of these galaxies, in order to better understand their formation and subsequent evolution.

This can be studied using various different diagnostics, including the location of galaxies on the stellar mass ($M_{\star}$) versus SFR plane. At a given redshift, normal star-forming galaxies form a so-called main sequence on this plane (with near constant specific star formation rate, sSFR $\equiv$ SFR/$M_{\star}$), whereas ‘starbursts’ are offset towards higher sSFRs by a factor of $> 2 - 4$ (Daddi et al. 2007; Noeske et al. 2007; González et al. 2011; Elbaz et al. 2011; Speagle et al. 2014). Hence, the location of submm galaxies in relation to the main sequence may tell us whether they are predominantly triggered by mergers, or alternatively are fed by (relatively steady) cold gas infall (the two options proposed by theoretical arguments: Swinbank et al. 2008; Dave et al. 2010; Narayanan et al. 2011, 2017; Ricciardelli et al. 2016; González et al. 2011; Hayward et al. 2011a,b, 2012; Cowley et al. 2015). This is because a major merger is a short-lived phenomenon, resulting in a substantial but temporary boost in SFR, potentially pushing a galaxy significantly above the main sequence (e.g. Hungr et al. 2013; cf. Förster Schreiber et al. 2009). Recent simulations show that high-redshift gas-rich mergers result in the SFR enhancement by a factor of $\sim 2 - 5$ (Fensch et al. 2017; their fig 5-7), so if submm galaxies are predominantly powered by major mergers, then they should by offset from the main sequence by this factor.

There is still some debate over whether submm galaxies lie above the main sequence, or simply form its high-mass end. This debate is not primarily concerned with the form of the main sequence, as most studies agree that, at high redshifts, the main sequence continues to extend to high stellar masses with SFR $\propto M_{\star}^{x}$, where $x$ is in the range $0.75 - 1.0$ (Karim et al. 2011; Speagle et al. 2014; Renzini & Peng 2015; Schreiber et al. 2015; Koprowski et al. 2013; Dunlop et al. 2017) with no evidence of any break as has been suggested at lower redshifts (Oliver et al. 2010; Whitaker et al. 2014; Ilbert et al. 2014; Lee et al. 2011; Tomczak et al. 2018; or from galaxy surveys based purely on optical data (Kochanek et al. 2012; Tasca et al. 2013). Based on morphological decomposition at low redshifts this break was shown to disappear when only disc (not bulge) stellar mass was used (Abramson et al. 2014). Low stellar mass estimates for submm galaxies lead to high sSFRs, above the main sequence (Hainline et al. 2011; Wardlow et al. 2011; Magelli et al. 2013; Casey et al. 2013), whereas higher derived stellar masses place submm galaxies on the main sequence (Michałowski et al. 2010a, 2010b; Yun et al. 2014; Johnson et al. 2013; Koprowski et al. 2014, 2016). In Michałowski et al. (2012a) we showed that this discrepancy results largely from different assumptions concerning the parametrization of star formation histories in the spectral energy distribution (SED) modelling. In particular, two-component star formation histories result in higher stellar masses. Such a choice assumes that galaxies before the beginning of the submm galaxy phase (either a peak of the gas accretion or a merger) have already built up a substantial fraction of their current stellar mass. In Michałowski et al. (2014a) we showed that two-component star formation histories (resulting in higher stellar masses) provide the most accurate stellar masses for a sample of simulated submm galaxies, which have properties that agree well with many properties of real submm galaxies (Michałowski et al. 2014b and references therein).

Hence, our studies of medium-size samples of around a hundred submm galaxies resulted in the conclusion that they form the high-mass end of the main sequence, at least at $z \lesssim 3 - 4$ (Michałowski et al. 2012a; Koprowski et al. 2014, 2016). A similar conclusion has been drawn from recent hydrodynamical simulations showing that all observational properties of submm galaxies can be explained by non-merging massive galaxies that sustain high SFRs for around 1 Gyr, and do not leave the main sequence during that time (Narayanan et al. 2013; see also Dâve et al. 2014; Hayward et al. 2011a; Shimizu et al. 2014). However, other simulations predict that a significant fraction of submm galaxies are powered by violent starbursts resulting from mergers (Baugh et al. 2005; Narayanan et al. 2013; Hayward et al. 2013). Further observational studies based on larger samples of submm galaxies are required to clarify this issue.

In addition, rather little is known about the very high-redshift ($z > 4$) tail of the submm galaxy population, because to date only a handful of submm sources have been confirmed at these extreme redshifts (Coppin et al. 2008, 2011; Schinnerer et al. 2008; Daddi et al. 2009; Knudsen et al. 2008, 2014; Riechers et al. 2010, 2013; Cox et al. 2011; Smolčić et al. 2011; Combes et al. 2012; Walter et al. 2012; Dowell et al. 2012; Watson et al. 2014). The discovery and study of such sources is difficult for several reasons. First, these very high-redshift sources are intrinsically rare, so very few of them are likely to be discovered in submm surveys covering only a few hundred square arcmin (as typically achieved at 850 $\mu$m prior to SCUBA-2). Secondly, the combined effects of extreme dust-obscuration and redshift mean that optical and radio counterparts can be extremely faint (e.g. Walter et al. 2012), and hence redshift information hard to secure. Moreover, the determination of redshifts at submm/mm wavelengths from carbon monoxide (CO) lines currently remains very time consuming for all but the brightest objects (Weiβ et al. 2009; Vicen et al. 2013) and hence is not practical for large samples. These difficulties, and the resulting small samples of confirmed high-redshift submm galaxies have also hampered the proper statistical investigation of suggestions that the brightest submm sources are preferentially found at the highest redshifts (Wright et al. 2004; Pope et al. 2003; Michałowski et al. 2012a; Koprowski et al. 2014; Simpson et al. 2014).

Our understanding of both the relation of submm galaxies with respect to the main sequence, and the prevalence and nature of the most extreme redshift submm sources can both be improved by the larger area submm surveys now being provided by SCUBA-2. Hence, here we use the largest deep survey at 850 $\mu$m undertaken to date, the SCUBA-2 Cosmology Legacy Survey (CLS). This survey is described, and the 850 $\mu$m catalogues are presented in Geach et al.

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Here we build on this work by attempting to determine the identifications, redshifts and physical properties of a statistically significant, well-defined sample of around 2000 submm galaxies detected in the full ~ 2 deg$^2$ of 850-µm imaging provided by the S2CLS across the UDS and COSMOS fields. A key objective of this study is to assemble a substantial but well-defined subsample of submm sources with complete redshift information, in order to better define the high-redshift tail of the population, and to clarify the extent to which submm galaxies can indeed be naturally explained by the high-mass end of the evolving main sequence of star-forming galaxies.

This paper is structured as follows. In Section 2 we summarise the submm imaging, and describe the supporting higher-resolution multiwavelength data (optical/near-IR/mid-IR/radio) that we utilise to establish the positions of the galaxy counterparts to the submm sources in the two survey fields. In Section 3 we describe the methods used to identify potential galaxy counterparts, and to assess their statistical significance/robustness. In Section 4 we then pause to revisit the results of existing ALMA follow-up of 29 of the sources in our sample, both to assess the robustness and completeness of our identification process, and to assess the impact of source multiplicity/blending on the reliability of the 850-µm source counts. In Section 5 we discuss and present the long-wavelength imaging available in our survey fields; such information is crucial for the estimation of redshifts for sources that lack optical/near-IR counterparts, and for the estimation of SFRs, and leads us to define a subset of 651 sources with the information required for an unbiased investigation of their physical properties (i.e. with $\geq 4\sigma$ detections at 850 µm, and sufficient multiwavelength data to yield complete/unbiased redshift information). The photometric redshifts, and source number density as a function of redshift are derived in Section 6, while SFRs and stellar masses are presented in Section 7. We discuss the implications of our results in Section 8, and close with our conclusions in Section 9.

Table 1. The 3σ depths of the multifrequency data used in the COSMOS and UDS fields.

<table>
<thead>
<tr>
<th>Filter</th>
<th>COSMOS</th>
<th>UDS</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>27.1</td>
<td>...</td>
<td>AB mag</td>
</tr>
<tr>
<td>B</td>
<td>...</td>
<td>27.8</td>
<td>AB mag</td>
</tr>
<tr>
<td>V</td>
<td>...</td>
<td>27.4</td>
<td>AB mag</td>
</tr>
<tr>
<td>g</td>
<td>27.2</td>
<td>...</td>
<td>AB mag</td>
</tr>
<tr>
<td>r</td>
<td>26.7</td>
<td>...</td>
<td>AB mag</td>
</tr>
<tr>
<td>R</td>
<td>...</td>
<td>27.1</td>
<td>AB mag</td>
</tr>
<tr>
<td>i</td>
<td>26.4</td>
<td>27.0</td>
<td>AB mag</td>
</tr>
<tr>
<td>z'</td>
<td>25.3</td>
<td>26.3</td>
<td>AB mag</td>
</tr>
<tr>
<td>Y</td>
<td>25.0/25.6$^a$</td>
<td>25.1</td>
<td>AB mag</td>
</tr>
<tr>
<td>J</td>
<td>24.9/25.2$^a$</td>
<td>25.6</td>
<td>AB mag</td>
</tr>
<tr>
<td>H</td>
<td>24.5/24.8$^a$</td>
<td>25.1</td>
<td>AB mag</td>
</tr>
<tr>
<td>K$_s$</td>
<td>24.0/24.9$^a$</td>
<td>25.2</td>
<td>AB mag</td>
</tr>
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<td>3.6 µm</td>
<td>0.17</td>
<td>0.18</td>
<td>µJy</td>
</tr>
<tr>
<td>4.5 µm</td>
<td>0.20</td>
<td>0.22</td>
<td>µJy</td>
</tr>
<tr>
<td>5.6 µm</td>
<td>0.6</td>
<td>19</td>
<td>µJy</td>
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<tr>
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<td>8.8</td>
<td>12</td>
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<td>30</td>
<td>µJy</td>
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<td>100 µm</td>
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<td>6.7</td>
<td>mJy</td>
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<td>mJy</td>
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<td>mJy</td>
</tr>
<tr>
<td>850 µm</td>
<td>4.3</td>
<td>2.7</td>
<td>mJy</td>
</tr>
<tr>
<td>1.1 mm</td>
<td>3.8</td>
<td>3.0–5.1</td>
<td>mJy</td>
</tr>
<tr>
<td>1.4 GHz</td>
<td>36</td>
<td>27</td>
<td>µJy</td>
</tr>
</tbody>
</table>

$^a$ The two alternative values correspond to the shallower and deeper strips of the UltraVISTA near-IR imaging.

2 DATA

2.1 Submm

We used the 850-µm data obtained with the James Clerk Maxwell Telescope (JCMT) equipped with the Submillimetre Common-User Bolometer Array 2 (SCUBA-2; Holland et al. 2013) within the Cosmology Legacy Survey (CLS; Geach et al. 2017). The SCUBA-2 data were reduced with the S2CLS$^2$ package V1.4.0 (Chaplin et al. 2013) with the flux calibration factor (FCF) of 337 Jy·pW$^{-1}$·beam$^{-1}$. The results from smaller, deeper sub-fields within the CLS have already been presented in Geach et al. (2013), Roseboom et al. (2013, Koprowski et al. (2016) and Zavala et al. (2017), while multiwavelength identifications (IDs) for the sources in the ~ 1 deg$^2$ UDS field have been provided by Chen et al. (2016).

The source S2CLSJ021830-053130 with an 850 µm flux of $\sim 3.8$ mJy was identified by Zavala et al. (2017), while multiwavelength identifications were presented in Geach et al. (2017), who extracted the sources with the S2CLS$^2$ package V1.4.0 (Chaplin et al. 2013) with the flux calibration factor (FCF) of 337 Jy·pW$^{-1}$·beam$^{-1}$.

The full width at half-maximum (FWHM) of the resulting 850 µm map is 14.6 arcsec.

For this study we have used the ‘wide’ SCUBA-2 850 µm maps of the COSMOS (1.22 deg$^2$ reaching $\sim 1.4$ mJy rms) and UDS (0.96 deg$^2$ reaching $\sim 0.9$ mJy rms) fields. They were selected because they are the two largest CLS fields corresponding to $\sim 70\%$ of the total survey area, and because in most of the other (smaller) fields the auxiliary data are shallower, making it more difficult to constrain physical properties of submm galaxies. The source catalogue is presented in Geach et al. (2017), who extracted the sources by searching for peaks in the beam-convolved map with a signal-to-noise ratio $\geq 3.5\sigma$. This process resulted in 726 and 1088 sources in the COSMOS and UDS fields, respectively. The source S2CLSJ021830-053130 with an 850 µm flux of $\sim 50$ mJy is the lensed candidate discussed by Ikarashi et al. (2017).

2.2 Radio and mid-infrared

The Karl G. Jansky Very Large Array (VLA) 1.4 GHz radio data were taken from Schinnerer et al. (2007, 2010) for the COSMOS field, and from Ivison et al. (2003, 2007) and Arumugam et al. (in preparation) for the UDS field. The catalogues include sources for which $\geq 3\sigma$ detections were obtained.

The mid-infrared (mid-IR) Spitzer data are from the Spitzer Extended Deep Survey (SEDS; Ashby et al. 2013), the Spitzer Large Area Survey with Hyper-Suprime-
Cam (SPASH, PI: P. Capak), the S-COSMOS project (Sanders et al. 2007; Le Floc’h et al. 2008), and the Spitzer Public Legacy Survey of the UKIDSS Ultra Deep Survey (SpUDS; PI: J. Dunlop) described in Caputi et al. (2011). To obtain the 3.6 and 4.5 μm photometry we used the de-confusion code T-PHO (Merlin et al. 2013). This utilises prior information on the positions and morphologies of objects from a high-resolution image (HRI; in this case the Spitzer imaging) while solving for the fluxes of these objects.

The 3σ depths of the VLA radio and Spitzer mid-IR imaging in both fields are summarised in Table 1.

2.3 Optical and near-infrared imaging

The optical data in both fields were obtained with Subaru/SuprimeCam (Miyazaki et al. 2002), as described in Dye et al. (2006) and Furusawa et al. (2008), and from the Canada-France-Hawaii Telescope Legacy Survey (CFHTLS), as described in Bowler et al. (2012). The deep z’-band images are described in Bowler et al. (2012) and Furusawa et al. (2016). The near-infrared (near-IR) data in the COSMOS field was obtained from Data Release 2 of the UltraVISTA survey (McCracken et al. 2012; Bowler et al. 2014), while in the UDS field the near-IR data were provided by Data Release 10 of the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007; Cirasuolo et al. 2011; Fontana et al. 2014).

In both fields the optical and near-IR fluxes were measured in 3-arcsec diameter apertures, and the resulting 3σ depths of this aperture photometry are summarised in Table 1.

Finally, we used a list of spectroscopic redshifts from 3D-HST (Brammer et al. 2012; Skelton et al. 2014; Momcheva et al. 2016), VIMOS Ultra-Deep Survey (VUDS; Le Fèvre et al. 2013; Tasca et al. 2017), zCOSMOS (Lilly et al. 2007, 2008), MOSFIRE Deep Evolution Field (MOSDEF; Kriek et al. 2014), PRISm Multi-object Survey (PRIMUS; Coil et al. 2011) and from Trump et al. (2009, 2014) in the COSMOS field and UDSz (Mclaren et al. 2013; Bradshaw et al. 2013; Almaini et al., in preparation) and VIMOS Public Extragalactic Redshift Survey (VIPERS; Guzzo et al. 2014) in the UDS field.

3 GALAXY IDENTIFICATIONS

As in Michałowski et al. (2012b), we obtained the radio, 24 μm and 8 μm counterparts applying the method outlined in Downes et al. (1986), Dunlop et al. (1983) and Ivison et al. (2007). We applied a uniform search radius of 8 arcsec, a conservatively high value in order to allow for astrometry shifts due to either pointing inaccuracies or source blending. This is an appropriate choice for the JCMT/SCUBA-2 850 μm beam FWHM of ≃ 15 arcsec, as ALMA observations have revealed the brightest submm sources up to approximately half the beam FWHM away from the original JCMT/SCUBA-2 and APEX/LABOCA positions (Simpson et al. 2015; Hodge et al. 2013).

The statistical significance of each potential counterpart was assessed on the basis of the corrected Poisson probability p that the chosen radio, 24 μm or 8 μm candidate could have been selected by chance. IDs with a probability of chance association of p ≲ 0.05 are deemed to be ‘robust’, whereas those with 0.05 < p < 0.1 are labelled as ‘tentative’. If the p values of multiple IDs for a given SCUBA-2 source satisfy these criteria, then all are retained, but the one with the lowest p value is used for subsequent analysis.

IDs for the SCUBA-2 sources in the UDS field based on radio and optical counterparts (utilising an optical/near-IR colour selection) have previously been presented by Chen et al. (2016). In this work, following our previous practice, we have complemented radio counterpart selection with searches for counterparts in the 24-μm and 8-μm Spitzer imaging. Nevertheless, the agreement between our IDs in the UDS field and those presented by Chen et al. (2016) is very good; restricting the SCUBA-2 sample to the 716 > 3σ objects in the UDS field, only 90 of our robust (p ≤ 0.05) primary IDs (with the lowest p) are not matched to those of Chen et al. (2016), and 29 of these 90 are assigned Class = 2 by Chen et al. (2016), meaning that the optical data were inadequate for searching for IDs for these sources in the Chen et al. (2016) study.

All of our IDs for the ≥ 3.5σ 850 μm sources in the COSMOS and UDS fields are presented in Tables A1 and A2 in the appendix, respectively.

We summarise the outcome of the identification process in Table 2 where we give the number of SCUBA-2 sources with IDs, and the nature of these IDs. We present the ID statistics split by ID wavelength and robustness, and also tabulate the results for three different significance cuts in the 850-μm source sample. The number of IDs as a function of the SCUBA-2 850 μm flux is plotted in Fig. 1 (shown here for the full ≥ 3.5σ SCUBA-2 sample). The ID rate is lower towards lower submm fluxes. This is expected, both because of the increasing prevalence of false and/or flux-boostered sources at low significance, but also because fainter submm galaxies have, on average, correspondingly lower radio and mid-IR fluxes (as expected if the SED shape does not vary strongly from source to source; see fig. 1 of Michałowski et al. 2012b and of Ibar et al. 2010).

Unsurprisingly, the fraction of SCUBA-2 sources that lack IDs is also a function of 850-μm S/N. As mentioned above, this is partly because the lower S/N sources are generally fainter, but also, as Geach et al. (2017) have shown from source injection and retrieval simulations, approximately 15–20 per cent of ≥ 3.5σ SCUBA-2 sources located by the peak-finding method in these wide-area survey fields are either completely erroneous or substantially flux-boostered. It is thus perhaps as expected that the unidentified fraction (with neither robust nor tentative IDs) drops from ≃ 35 per cent at S/N ≳ 3.5 to ≃ 20 per cent at S/N ≳ 5.0 (where the percentage of false positive sources is expected to be < 1 per cent; Geach et al. 2017). Despite this, we provide the IDs for all sources in the 3.5σ catalogue because, as Table 2 quantifies, the extended sample provides a large number of additional robust identifications worthy of further study and
Table 2. Galaxy counterpart identification statistics for SCUBA-2 sources in the UDS and COSMOS fields, detailing success rates for both robust and tentative IDs, split by wavelength, and also tabulated for three different significance cuts in the original 850-µm sample.

<table>
<thead>
<tr>
<th>Field</th>
<th>N</th>
<th>rob. ID %</th>
<th>tent. ID %</th>
<th>No. ID</th>
<th>N₁₄ %</th>
<th>rob₁₄ %</th>
<th>tent₁₄ %</th>
<th>N₂₄ %</th>
<th>rob₂₄ %</th>
<th>tent₂₄ %</th>
<th>N₈₀ %</th>
<th>rob₈₀ %</th>
<th>tent₈₀ %</th>
<th>Nopt</th>
<th>zopt %</th>
</tr>
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<tbody>
<tr>
<td>COSMOS</td>
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<td>700 (0)</td>
<td>694 (25)</td>
<td>24 (2)</td>
<td>111 (16)</td>
<td>111 (16)</td>
<td>719 (26)</td>
<td>137 (19)</td>
<td>448 (69)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UDS</td>
<td>1088</td>
<td>694 (24)</td>
<td>1084 (33)</td>
<td>307 (28)</td>
<td>172 (18)</td>
<td>951 (27)</td>
<td>191 (20)</td>
<td>968 (64)</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Both</td>
<td>1814</td>
<td>1163 (65)</td>
<td>1787 (25)</td>
<td>488 (27)</td>
<td>283 (17)</td>
<td>1670 (20)</td>
<td>328 (22)</td>
<td>1416 (65)</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>S/N &gt; 3.5</td>
<td>COSMOS</td>
<td>254 (35)</td>
<td>604 (22)</td>
<td>181 (26)</td>
<td>709 (26)</td>
<td>719 (26)</td>
<td>137 (19)</td>
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<tr>
<td>UDS</td>
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<td>1163 (65)</td>
<td>1787 (25)</td>
<td>488 (27)</td>
<td>283 (17)</td>
<td>1670 (20)</td>
<td>328 (22)</td>
<td>1416 (65)</td>
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<td>29 (16)</td>
<td>392 (49)</td>
<td>133 (62)</td>
<td>181 (62)</td>
<td>137 (22)</td>
<td>643 (68)</td>
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<tr>
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<td>204 (28)</td>
<td>307 (28)</td>
<td>315 (48)</td>
<td>621 (22)</td>
<td>137 (22)</td>
<td>643 (68)</td>
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<td>65 (21)</td>
<td>72 (24)</td>
<td>309 (71)</td>
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<tr>
<td>UDS</td>
<td>232 (32)</td>
<td>105 (35)</td>
<td>105 (35)</td>
<td>72 (24)</td>
<td>309 (71)</td>
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</table>

(1) field name; (2) the total number of SCUBA-2 sources, (3) the number of sources with IDs having at least one robust association with \( p \leq 0.05 \) at radio, 24-µm, or 8.0-µm; (4) the number of sources with IDs having at least one tentative counterpart with \( 0.05 < p < 0.1 \); (5) the number of SCUBA-2 sources covered by the radio map (for which radio IDs can in principle be obtained); (6) and (8) the number of robust and tentative 1.4 GHz IDs; (9) the number of SCUBA-2 sources covered by the 24-µm map (for which 24-µm IDs can in principle be obtained); (10) and (11) the number of robust and tentative 24-µm IDs; (12) the number of SCUBA-2 sources covered by the 8.0-µm map (for which 8.0-µm IDs can in principle be obtained); (13) and (14) the number of robust and tentative 8.0-µm IDs; (15) the number of SCUBA-2 sources covered by the optical map (for which optical redshift can in principle be derived); (16) the number of SCUBA-2 sources with the best ID having an optical redshift. In the parentheses the percentage of IDs are shown.

Figure 1. The number of IDs as a function of SCUBA-2 850-µm flux density for the COSMOS and the UDS fields (left and right, respectively). The red histogram shows the number of SCUBA-2 sources with radio IDs. The space between the red histogram and the blue histogram shows the number of SCUBA-2 sources with 24-µm IDs but no radio IDs. The space between the blue histogram and the green histogram shows the number of SCUBA-2 sources with only 8-µm IDs. The space between the green histogram and the black histogram shows the number of SCUBA-2 sources with no IDs. The upper panels take into account all IDs, whereas the lower panels take into account only robust (\( p < 0.05 \)) IDs. The sharp decline in the number of sources in the UDS field below 3 mJy reflects the highly uniform depth of the SCUBA-2 map in this field. This map is also deeper than that of the COSMOS field. The histograms shown here contain all 1814 sources in the full \( \geq 3.5\sigma \) SCUBA-2 sample.
follow-up. We therefore provide positions of all new IDs in the appendix.

Nevertheless, it would clearly be wrong to infer that the real fraction of unidentified sources is as large as \( \approx 35 \) per cent, when the evidence from the higher S/N cuts suggests the true figure is \( \approx 20 \) – \( 25 \) per cent. Consequently, for the remainder of the analysis in this paper we consider only sources with S/N \( \geq 4.0 \) (where the false positive SCUBA-2 source rate is expected to be \( \approx 5 \) per cent; Leigh et al. 2013). At this S/N threshold, Table 2 shows we have robust IDs for \( \approx 60 \) per cent of the 1121 sources, with an additional \( \approx 15 \) per cent having tentative IDs, and hence \( \approx 25 \) per cent of sources remaining unidentified. About half of the robust IDs are provided by the 1.4 GHz radio imaging, and so extending the ID process to search for counterparts in the 24-\( \mu \)m and 8-\( \mu \)m imaging has had a significant positive impact. We note that the ID statistics in the COSMOS and UDS fields are statistically consistent (due to the homogeneity of the SCUBA-2 data set, and the similar quality of the UDS fields are statistically consistent (due to the homogeneity of the SCUBA-2 data set, and the similar quality of the UDS fields).

In summary, we have completed the ID process and, for the \( \approx 1000 \)-source \( \geq 4 \) \( \mu \)Jy 850-\( \mu \)m sample, have identified \( \approx 75 \) per cent of the sources. A key question, then, is why \( \approx 25 \) per cent of the SCUBA-2 sources remain unidentified. There are several possible factors. First, some small remaining subset of these sources may not be real. Secondly, as discussed further below, a few of these sources may in fact be blends of 2 or 3 significantly fainter sources, for which the optical/IR/radio counterparts lie below the flux-density limits of the supporting data; this is arguably not a serious problem since such sources should not really be retained in a bright flux-limited sample. Finally, some of the unidentified sources are likely to lie at higher redshifts where the resulting radio and mid-IR flux densities are too faint for their counterparts to be uncovered in the existing VLA and Spitzer imaging (which, unlike the submm imaging, does not benefit from a negative \( k \)-correction). In the following sections we explore these issues further, first by revisiting the results of ALMA follow-up of a subset of the SCUBA-2 sources, and then by exploiting the available long-wavelength (FIR-\( \mu \)m) data in the field to attempt to constrain the redshifts of the unidentified SCUBA-2 sources.

4 COMPARISON WITH ALMA FOLLOW-UP

4.1 Validation of galaxy identifications

We can estimate the completeness and reliability of our identification procedure by considering the subsample of 29 SCUBA-2 sources in our sample that has already been the subject of deep ALMA follow-up imaging (Simpson et al. 2015b). Although this subsample was originally selected to contain the brightest SCUBA-2 sources in the UDS field, the final deeper imaging from the S2CLS corrects for some of the more severe flux-boosting effects in the earlier map, with the consequence that this subset of sources actually contains objects with flux densities extending down to the flux-density limit of our sample (and is thus more representative of the overall sample than originally anticipated).

In Fig. 2 we plot the ALMA flux densities of all 52 ALMA galaxies versus the SCUBA-2 flux densities of the corresponding SCUBA-2 sources and highlight in blue where, utilising the radio/mid-IR ID method adopted here, we have successfully located the position of the galaxy counterpart as confirmed by ALMA. For many of the sources the ALMA imaging has revealed more than one submm component, and in Fig. 2 we show this by connecting ALMA subcomponents with solid vertical lines. In the majority of cases it can be seen that the secondary ALMA component is a much fainter (\( \approx 1 \)–\( 2 \) mJy) object in the field. Moreover, the flux densities of the secondary components are not correlated with the brighter component flux densities, whereas the secondary ALMA and SCUBA-2 flux densities of the brighter components are well correlated and frequently near equal (as indicated by the diagonal dashed line). For 25 of the 29 SCUBA-2 sources, our radio+mid-IR identification process correctly locates the position of the dominant ALMA component, yielding an estimated completeness of \( \approx 86 \) per cent.

Figure 2. The ALMA flux densities for ALMA sources (red and blue squares) revealed through the follow-up of 29 SCUBA-2 sources in the UDS field (Simpson et al. 2015b), plotted against the SCUBA-2 single-dish flux density of each source as derived from the final SCUBA-2 CLS 850-\( \mu \)m imaging of the UDS field. The ALMA sources lying within the SCUBA-2 FWHM in the follow-up imaging are connected by solid vertical lines, and the blue squares indicate which of the ALMA sources was identified by our radio+mid-IR identification process as the location of the galaxy making the dominant contribution to the SCUBA-2 submm source. Although the brightest SCUBA-2 source divides into two ALMA subcomponents of comparable flux density, it can be seen that, in the vast majority of cases, the secondary ALMA component is a much fainter (\( \approx 1 \)–\( 2 \) mJy) object in the field. Moreover, the flux densities of the secondary components are not correlated with the brighter component flux densities, whereas the secondary ALMA and SCUBA-2 flux densities of the brighter components are well correlated and frequently near equal (as indicated by the diagonal dashed line). For 25 of the 29 SCUBA-2 sources, our radio+mid-IR identification process correctly locates the position of the dominant ALMA component, yielding an estimated completeness of \( \approx 86 \) per cent.


4.2 Multiplicity and number counts

First with the IRAM PdB and the SMA, and more recently with ALMA, it has now become possible to address the issue of the extent to which the submm galaxies detected by single-dish surveys consist of blends of fainter submm galaxies lying within the single-dish primary beam (Wang et al. 2015b; Hodge et al. 2013; Karim et al. 2013; Simpson et al. 2015b). Most of these studies reported a very high (> 50%) multiplicity rate, but this was based on including even the faintest submm companions in the statistics, and in several cases the single-dish beamsize was also significantly larger than delivered by the JCMT at 850 μm. In what follows we revise these numbers by treating as multiple only the cases when the secondary companion is sufficiently bright to potentially affect the identifications if only single-dish observations were available. The impact of real physical associations, or simply the blending of projected sources (i.e. at very different redshifts) on single-dish flux densities and derived number counts is obviously a function of the size (i.e. FWHM) of the single dish primary beam, and hence is more serious for surveys conducted at longer wavelengths, or with smaller telescopes.

In the LABOCA Extended Chandra Deep Field South submm survey (LESS; Weiss et al. 2009b), 20 out of 69 LABOCA submm sources (≃ 30 per cent) were revealed by ALMA follow-up imaging to comprise multiple ALMA sources with a flux-density ratio < 3, leading to suggestions that source multiplicity might be a serious problem for previous single-dish submm surveys (Hodge et al. 2013; Karim et al. 2013; Lambas et al. 2012), and also provides a reasonable threshold for considering which sources have had their single-dish flux-densities and positions seriously affected by source multiplicity/blending. A slightly smaller fraction (16 of these 69, ≃ 23 per cent) of these sources were also found to have multiple radio IDs (Bigs et al. 2011).

However, the beam area of APEX/LABOCA is nearly twice as large as that of JCMT/SCUBA-2, so the impact of source multiplicity on the SCUBA-2 results is expected to be significantly smaller. This is confirmed by the ALMA follow-up of the SCUBA-2 sources by (Simpson et al. 2015b), as already presented in Fig. 2. Here only 6 out 30 (≃ 20 per cent) of the SCUBA-2 sources have been found to consist of multiple ALMA sources with a flux-density ratio < 3, and arguably this is an overestimate for the full SCUBA-2 source sample, given that the sample studied by Karim et al. (2013) is biased towards brighter sources where blending is likely to be a more serious issue (due to the steep slope at the bright end of the submm luminosity function). Indeed, as is evident from Fig. 4, while the brightest SCUBA-2-source is clearly revealed to be a blend of two ALMA components with comparable flux densities, the majority of SCUBA-2 source flux densities are well matched by the flux densities out of 69 LABOCA sources, yielding a completeness of ≃ 75 per cent. This is higher than the completeness quoted by Hodge et al. 2013, but they included all ALMA sources, not just the brightest ones for each LABOCA source. Our approach gives the fraction of single-dish sources for which the main component was correctly identified.

Figure 3. The cumulative distribution of single-dish JCMT/SCUBA-2 850-μm flux densities (blue) and interferometric ALMA flux densities (red) resulting from the follow-up imaging of 29 SCUBA-2 sources in the UDS field (Simpson et al. 2015b), as already illustrated in Fig. 2. Although the ALMA imaging reveals a population of fainter sources lying below the flux-density limit of the SCUBA-2 imaging, the bright end of the source counts is relatively little affected by whether one utilises the original SCUBA-2 flux densities, or those of the brighter ALMA subcomponents. Even without any correction, the flux distributions brightwards of $\tilde{S}_{850} \approx 4$ mJy are not significantly different (application of the Kolmogorov-Smirnov test yields a probability of only 50 per cent that the ALMA and SCUBA-2 flux densities are not drawn from the same parent population), but application of a modest correction, either subtracting $\approx 1$ mJy from all SCUBA-2 flux densities or, as shown here, multiplying the SCUBA-2 flux densities by 0.9 (green distribution) is sufficient to bring the SCUBA-2 and ALMA bright source counts into near perfect agreement.
of the brighter ALMA components, and it is clear that in most cases the secondary ALMA component is either too faint, or too well-separated from the brighter component to significantly contaminate/bias the SCUBA-2 derived flux density.

We can also explore the issue of multiplicity from a radio perspective, by considering the prevalence of multiple radio IDs within the SCUBA-2 sample. If a submm source is composed of two or more sources with similar luminosities at similar redshifts, then if the primary component is detected in the radio with high signal-to-noise ratio, then the secondary component should also be detected. However, in the COSMOS (UDS) field, out of 181 (332) SCUBA-2 sources with radio IDs, only 14 (26) have multiple radio IDs, i.e. \( \gtrsim 8 \) per cent (8 per cent). For 14 (18) of them the secondary ID is also robust. The corresponding numbers for \( \gtrsim 4 \)\( \sigma \) SCUBA-2 sources are 7 per cent, or 27/401, 8 with robust secondary IDs (6 per cent or 33/587, 5 with robust secondary IDs). Finally, 9 per cent or 30/326, 5 with robust secondary IDs (10 per cent or 45/452, 6 with robust secondary IDs) of \( \gtrsim 8 \)\( \mu \)m IDs are multiple. However, the true multiplicity rate is likely higher, because unidentified sources could also represent blends of fainter submm sources. Hence, to better assess the ID multiplicity rate, we confined our attention to a subsample with high radio ID completeness. Among the twenty \( \gtrsim 10\sigma \) SCUBA-2 sources in the UDS field (85 per cent) have radio IDs and only 2/17 of these (i.e. 12 per cent) are multiple. An upper limit on multiplicity can be derived by assuming that all sources lacking a radio are multiple, yielding \( (2 + 3)/20 \) (i.e. 25 per cent).

We conclude that, within our SCUBA-2 sample, only \( \gtrsim 15–20 \) per cent of sources are potentially significantly affected by multiplicity and blending. Moreover, as we show in Fig. in the paper, the impact of any multiplicity/blending on the bright-end of the 850-\( \mu \)m source counts as derived from SCUBA and SCUBA-2 surveys with the JCMT is very modest. This shows that, even without any correction, the SCUBA-2 and ALMA flux-density distributions brightwards of \( S_{850} \sim 4 \) mJy are not significantly different (application of the Kolmogorov-Smirnov test yields a probability of only 50 per cent that the ALMA and SCUBA-2 flux densities are not drawn from the same parent population), and that application of a modest correction, either subtracting \( \leq 1 \) mJy from all SCUBA-2 flux densities or, as shown in Fig. in the paper, multiples the SCUBA-2 flux densities by 0.9, is sufficient to bring the SCUBA-2 and ALMA bright source counts into near perfect agreement. Our findings on the small impact of multiplicity on number counts are in agreement with those of in the paper, in which they found only \( \sim 15\% \) of their SMA-targeted SCUBA-2 submm sources are multiples, and therefore their SCUBA-2 counts are not significantly affected by multiplicity either. Previous claims that submm number counts have been severely biased by source blending appear to have been exaggerated, and in any case have generally been based on samples derived from imaging surveys with much larger beam sizes than are provided by the JCMT at 850 \( \mu \)m.

To summarise, given the success of our ID procedure in locating the positions of the brightest ALMA components, the relatively low prevalence of significant ALMA subcomponents or secondary radio IDs, and the modest impact of source multiplicity on the bright end of the 850-\( \mu \)m source counts, it is clear that source multiplicity and blending is not a serious issue for the study of bright 850-\( \mu \)m sources selected at the angular resolution provided by the JCMT.

5 LONG-WAVELENGTH PHOTOMETRY

We now return to the issue of completing the redshift content of the SCUBA-2 sample, and determining the physical properties of the sources. Because \( \sim 25 \) per cent of even the \( \gtrsim 4 \)\( \sigma \) SCUBA-2 sources remain unidentified at optical/near-IR/mid-IR/radio wavelengths, and because some of the optical identifications may be wrong (either because they are not statistically robust, or because they are intervening lenses) it is crucial to utilise the available far-infrared and mm imaging available in the field to enable at least crude constraints on redshift to be established (by fitting to the anticipated rest-frame far-infrared SED of the dust emission). This information is also important, even for the identified sources, for estimating the dust-enshrouded SFR of each object.

We therefore used the Herschel Data Base in Marseille (HeDaM) and the PACS Evolutionary Probe (PEP) in Marseille (Mahtani et al. 2011) and the PACS Evolutionary Probe (PEP; Lutz et al. 2011) data obtained with the Spectral and Photometric Imaging Receiver (SPIRE; Griffin et al. 2010) and the Photodetector Array Camera and Spectrometer (PACS; Poglitsch et al. 2010), covering the entire COSMOS and UDS fields. We used maps at 100, 160, 250, 350 and 500 \( \mu \)m with beam sizes of 7.4, 11.3, 18.2, 24.9 and 36.3 arcsec. The maps are available through the Herschel Database in Marseille (HeDaM) and the PEP website.

In addition, in order to constrain the long-wavelength side of the SEDs of SCUBA-2 sources, we used the 1.1 mm AzTEC imaging data available in both survey fields. This imaging unfortunately does not cover all of the area surveyed with SCUBA-2, and is less deep than is desirable, but nevertheless is provides detections for some of our 850-\( \mu \)m-selected galaxies, and useful upper limits for a significant fraction of the remainder. For the COSMOS field we used the JCMT and ASTE AzTEC (Wilson et al. 2008) maps and catalogues from Scott et al. (2008), and Aretxaga et al. (2011), covering 0.15 and 0.72\( \deg^2 \) down to an rms of 1.3 and 1.26 mJy beam\(^{-1}\), respectively. For the UDS field we used the JCMT and ASTE AzTEC data from Austermann et al. (2010) and Kohno (private communication). These cover 0.7 and 0.27\( \deg^2 \) to an rms depth of 1.0–1.7 and 0.5 mJy beam\(^{-1}\), respectively.

We obtained the Herschel fluxes of each SCUBA-2 source in the following way. We extracted 120-arcsec wide stamps from all five Herschel maps around the position of each SCUBA-2 source. Then we processed the PACS (100 and 160 \( \mu \)m) maps by simultaneously fitting Gaussians with the FWHM of the respective maps, centred at the positions of all radio and 24-\( \mu \)m sources located within these cut-outs.
and at the positions of the SCUBA-2 IDs. Then, to deconvolve the SPIRE (250, 350 and 500 μm) maps in a similar way, we used the positions of the 24-μm sources detected with PACS (>3σ), the positions of all radio sources, and the SCUBA-2 ID positions (or the submm positions if no radio or mid-IR ID had been secured). The errors were computed from the covariance matrix of the fit, in which the free parameters are simply the heights of the Gaussian beams fitted at each input position. Then the confusion noise of 5.8, 6.3 and 6.8 mJy beam\(^{-1}\) at 250, 350 and 500 μm, respectively, was added in quadrature. The fitting was performed using the IDL MPFIT package (Markwardt 2009).

To incorporate the information from the AzTEC imaging, we matched the SCUBA-2 and 1.1 mm catalogues within 12 arcsec (the approximate sum in quadrature of the positional uncertainties of SCUBA-2 and AzTEC sources), which resulted in 72 matches in the COSMOS field, and 118 matches in the UDS field. Then we estimated the 1.1 mm fluxes for the non-matched SCUBA-2 sources in the same way as for the Herschel fluxes. This was possible for an additional 211 SCUBA-2 sources in the COSMOS field and 250 SCUBA-2 sources in the UDS field.

The derived long-wavelength fluxes are presented in Tables A3 and A4 in the appendix.

Because the 1.1-mm information proves to be crucial for setting meaningful upper bounds on the ‘long-wavelength’ redshift estimates (particularly for SCUBA-2 sources with weak, or non-existent Herschel detections), we have restricted the remainder of the analysis presented in this paper to the subset of 651 (out of 1121) ≥ 4σ SCUBA-2 sources for which the AzTEC 1.1-mm coverage is available (283 in the COSMOS field and 368 in the UDS field).

6 REDSHIFTS AND NUMBER DENSITY

We used the optical, near-IR and IRAC data (presented in Tables A3 and A4 in the appendix) to fit the SEDs of all IDs and to derive their photometric redshifts and physical properties using the method of Cirasuolo et al. (2007, 2011). This uses a modification of the HYPERZ package (Bolzonella et al. 2000) with the stellar population models of Bruzual & Charlot (2003) and a Chabrier (2003) initial mass function (IMF) with a mass range 0.1–100 M\(_{\odot}\). A double-burst star formation history was assumed, but this choice has little impact on derived redshifts (as opposed to derived stellar masses, which are well reproduced by the two-component star formation history for submm galaxies; Michelakos et al. 2012a, 2014d). The metallicity was fixed at the solar value and reddening was calculated following the Calzetti et al. (2000) law within the range 0 ≤ A_V ≤ 6 (see Dunlop et al. 2007). The age of the young stellar component was varied between 50 Myr and 1.5 Gyr, and the old component was allowed to contribute 0–100 per cent of the near-IR emission while its age was varied over the range 1–6 Gyr. The HI absorption along the line of sight was included according to the prescription of Madau (1995). The accuracy of the photometric catalogue of Cirasuolo et al. (2010) is excellent, with a mean |\(z_\text{phot} - z_\text{spec}\)/(1 + z_\text{spec})| = 0.008 ± 0.034.

We also estimated ‘long-wavelength’ redshifts, as in Koprowski et al. (2014, 2016), fitting the average submm galaxy template (from the Herschel PACS, SPIRE, SCUBA-2 and AzTEC data). Non-detections were treated in the same way as detections in the fitting, using the flux and error measured at a given position. Hence, for the case of Herschel non-detections resulted in ruling out low-z solutions and flat \(\chi^2\) distributions at high redshifts. Long-wavelength redshifts were especially useful for sources with no optical counterparts (or no IDs at all). This redshift determination is obviously not as accurate as the optical photometric method, but provides an important estimate of the Δz ≃ 0.5-wide redshift bin within which a given source resides. For sources with optical/near-IR redshifts the median |\(z_\text{LW} - z_\text{opt}\)/(1 + z_\text{opt})| for the COSMOS field is ≃ 0.16 ± 0.03, while for the UDS field it is ≃ 0.011 ± 0.016. This is similar to the accuracy reported in Aretxaga et al. (2005, 2007).

For both redshift estimates the errors were calculated by the determination of the redshift range over which \(\chi^2\) increases by 1 from the minimum value while allowing all other parameters to vary.

The resulting redshifts are given in Tables A7 and A8 in the appendix. For sources with multiple IDs, the ID with the smallest \(p\)-value was used. The fraction of SCUBA-2 sources with optical/near-IR redshifts is summarised in Table B (column 16). We obtained optical/near-IR photometric redshift estimates for ≃ 60 per cent of the SCUBA-2 sources located

\[ z_{\text{opt}} = z_{\text{LW}} ± \Delta z \]

\[ z_{\text{LW}} = z_{\text{opt}} ± \Delta z \]

Figure 4. Long-wavelength photometric redshift as a function of optical/near-IR photometric redshift (Section 6) for the ≥ 4σ SCUBA-2 sources in the COSMOS (red) and UDS (blue) fields that have 1.1 mm coverage and optical/near-IR galaxy counterparts. The solid line represent \(z_{\text{LW}} = z_{\text{opt}}\), whereas the dashed lines show the 2σ cut from the Gaussian fit presented in Fig. A. Thinner symbols (above the upper dashed line) represent objects for which the long-wavelength redshifts were adopted (see Section 7). The concentration of points at \(z_{\text{LW}} = 3.9\) is due to Herschel-undetected objects for which the minimum \(\chi^2\) yielded by the long-wavelength fitting is almost flat above some lowest permitted value, and the formal best-fitting solution is at that lowest allowed redshift.
likely a foreground galaxy lens. The resulting final redshift distribution of the SCUBA-2 sources that have 1.1 mm coverage.

Table 3. Median properties of \( \geq 4\sigma \) SCUBA2 sources with 1.1 mm coverage.

<table>
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<th>Field</th>
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<th>z_{opt}</th>
<th>SFR</th>
<th>SFR_{z_{opt}}</th>
<th>log(M_{star}/M_{\odot})</th>
<th>sSFR</th>
<th>f_{old}</th>
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<td>(1)</td>
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<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
<td>(7)</td>
</tr>
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<td>COSMOS</td>
<td>2.40^{+0.11}_{-0.12}</td>
<td>2.11^{+0.04}_{-0.03}</td>
<td>324^{+8}_{-10}</td>
<td>301^{+7}_{-14}</td>
<td>11.11^{+0.05}_{-0.14}</td>
<td>2.12^{+0.13}_{-0.17}</td>
<td>0.75^{+0.08}_{-0.03}</td>
</tr>
<tr>
<td>UDS</td>
<td>2.42^{+0.12}_{-0.06}</td>
<td>2.24^{+0.04}_{-0.04}</td>
<td>261^{+6}_{-16}</td>
<td>258^{+6}_{-16}</td>
<td>11.13^{+0.02}_{-0.01}</td>
<td>1.97^{+0.14}_{-0.11}</td>
<td>0.93^{+0.01}_{-0.01}</td>
</tr>
<tr>
<td>Both</td>
<td>2.40^{+0.10}_{-0.04}</td>
<td>2.17^{+0.04}_{-0.04}</td>
<td>287^{+7}_{-16}</td>
<td>269^{+13}_{-7}</td>
<td>11.12^{+0.02}_{-0.02}</td>
<td>2.02^{+0.08}_{-0.08}</td>
<td>0.91^{+0.01}_{-0.02}</td>
</tr>
</tbody>
</table>

(1) Field name; (2) Median redshift including all sources; (3) Median optical photometric redshift; (4) Median SFR including all objects (using long-wavelength redshifts if optical redshifts are not available); (5) Median SFR including only objects with optical photometric redshifts; (6) Median stellar mass; (7) Median specific SFR. (8) Fraction of stellar mass contributed by the old stellar component (see Section 4).

For all properties but redshift only objects at \( z > 1 \) were taken into account.

inside the deep optical/near-IR imaging maps. The remaining \( \simeq 40 \) per cent either do not have IDs at all, or no optical source was matched to the radio/mid-IR IDs.

For 50 IDs in the COSMOS field and 20 in the UDS spectroscopic redshifts (Section 2.3) were available and used instead of optical photometric redshifts.

As in Koprowski et al. (2016), we attempted to filter the optical/near-IR redshifts, replacing these redshift estimates with the long-wavelength photometric redshift values when the two values are formally inconsistent. In practice, where the two values differ dramatically, it is in the sense that the optical/near-IR photometric redshift estimate is too low, either because the optical counterpart has been assigned in error, or because the identified optical galaxy is in fact lensing a more distant submm source (as in Negrello et al. 2010).

In Fig. 4 we show the long-wavelength redshift as a function of optical redshift, and in Fig. 5 we show the distribution of the difference between the long-wavelength and optical redshifts, \( (z_{LW} - z_{opt})/(1 + z_{opt}) \).

We fitted a Gaussian to the negative side of the distribution obtaining a width of \( \sigma = 0.23 \). Then we discarded optical/near-IR photometric redshifts (and the corresponding IDs) for sources with long-wavelength redshifts that are \( 2\sigma \) higher (above the dashed lines in Figs 4 and 5), and thereafter retain only the long-wavelength redshift estimates for these sources. This happened for 23 robust and 14 tentative primary IDs in the COSMOS field and 42 robust and 11 tentative primary IDs in the UDS field. Out of 651 \( \geq 4\sigma \) sources with 1.1 mm coverage 349 have optical counterparts retained in the analysis because of the consistency with the long-wavelength redshift (160 in the COSMOS field and 189 in the UDS field).

The substantial scatter in the \( z_{LW} \) versus \( z_{opt} \) plot (Fig. 4) can be fully explained by photometry measurement errors. The median contribution of the data points to the \( \chi^2 \) with respect to the \( z_{LW} = z_{opt} \) line is \( \sim 1.5 \), so this model explains the data reasonably well. This justifies our choice of a single template in deriving \( z_{LW} \), as the data do not require a more complex model.

The resulting final redshift distribution of the SCUBA-2 sources is shown in Fig. 6 sub-divided by the type of redshift calculation (all, optical/near-IR, long-wavelength), by the survey field, and by the quality of the ID. The median redshift for the full \( \geq 4\sigma \) SCUBA2-2 sample with 1.1-mm coverage is \( z = 2.40^{+0.10}_{-0.04} \) for all sources, or \( z = 2.17 \pm 0.04 \) for the subset of sources with retained optical/near-IR redshifts (see Table 3), consistent with previous studies of
 shifts, as much as 393 out of 1691 (23 per cent) SCUBA-2 into account both optical/near-IR and long-wavelength redshifts, higher redshifts than the remaining sample. Taking into account both optical/near-IR and long-wavelength redshifts (red dotted line), and those with long-wavelength redshifts only (red dotted line). Middle: the redshift distribution divided by field. The line type is the same as in the top panel: solid lines denote all redshifts, and dashed lines denote optical/near-IR redshifts. The lines are colour-coded by the field: black: both fields, red: COSMOS, blue: UDS. Bottom: the redshift distribution divided by the quality of IDs. The black solid line is the same as above, whereas the blue dashed line denotes robust IDs (p < 0.05), and the red dotted line denotes tentative IDs (0.05 < p < 0.1).

The redshift distribution of the > 4σ SCUBA-2 sources that have 1.1 mm coverage showing all sources (black solid line), those with optical/near-IR redshifts (blue dashed line), and those with long-wavelength redshifts only (red dotted line). Middle: the redshift distribution divided by field. The line type is the same as in the top panel: solid lines denote all redshifts, and dashed lines denote optical/near-IR redshifts. The lines are colour-coded by the field: black: both fields, red: COSMOS, blue: UDS. Bottom: the redshift distribution divided by the quality of IDs. The black solid line is the same as above, whereas the blue dashed line denotes robust IDs (p < 0.05), and the red dotted line denotes tentative IDs (0.05 < p < 0.1).

While the median redshifts are consistent with previous studies, our large sample size, and the use of long-wavelength photometric redshifts to complete the redshift content of the sample, has enabled us to more clearly reveal/define the extent of the high-redshift tail of the submm galaxy population. Obviously, sources with no optical/near-IR redshifts (red dotted histogram on the top panel of Fig. 8) have, on average, higher redshifts than the remaining sample. Taking into account both optical/near-IR and long-wavelength redshifts, as much as 393 out of 1691 (23 per cent) SCUBA-2 sources are at z > 4. However, only 39 sources (10 in COSMOS and 29 in UDS field) have optical/near-IR z > 4. Similarly, out of 651 > 4σ SCUBA-2 sources with 1.1 mm coverage, 93 (14 per cent) are at z > 4 and 19 have optical/near-IR z > 4 (6 in COSMOS and 13 in the UDS field).

The middle panel of Fig. 8 shows that the redshift distributions in the COSMOS and UDS fields separately (both using all redshifts and only optical redshifts) are qualitatively similar, displaying a peak at z ≈ 2. This means that with ≈ 1 deg² fields we start to overcome the cosmic variance, which makes number counts (Scott et al. 2011, 2012) and redshift distributions (Michałowski et al. 2012) derived using smaller fields significantly different from each other. Application of the Kolmogorov-Smirnov test results in probability of ≥ 0.7 per cent that the COSMOS and UDS samples are drawn from the same parent population, but this is a ≤ 3σ discrepancy.

The redshift distribution of tentative IDs (0.05 < p ≤ 0.1, red dotted histogram on the bottom panel of Fig. 8) is not shifted towards lower redshifts with respect to robust IDs (p ≤ 0.05, blue dashed line), as would be expected if tentative IDs were significantly contaminated by unrelated galaxies (because lower-redshift galaxies dominate optical catalogues). In any case, the fraction of tentative IDs is only ≈ 15 per cent (Table 2 both before and after long-wavelength redshift filtering), so they do not significantly affect our conclusions.

It has been suggested in the past that submm
galaxies with higher fluxes are located at preferentially at higher redshifts (Ivison et al. 2002; Pope et al. 2002; Michałowski et al. 2012b; Koprowski et al. 2014), and with our large sample we are able to further investigate this issue. Fig. 7 shows submm flux as a function of redshift for the SCUBA-2 sources presented here and in a deeper SCUBA-2 image in the COSMOS field (Koprowski et al. 2016). It is evident that the bottom-right corner of this plot (high flux density, low redshift) is empty, and this is due not to selection effects, as such sources should be easy to detect at all wavelengths, and redshifts easy to measure. The scatter in this figure is large but a weak overall trend can be discerned. The Spearman rank correlation coefficient is 0.19 with a very small probability ($\sim 3 \times 10^{-7}$) of the null hypothesis (no correlation) being acceptable. However, there is no real evidence for a deficit of lower luminosity objects at high-redshift, and so this statistically significant correlation is driven by the absence of submm bright low-redshift objects; very luminous submm galaxies are only found in our survey at $z > 2$.

In Fig. 8 we utilise the redshift content of our SCUBA-2 sample to plot the comoving number density of submm galaxies with SFR $> 300 \, M_\odot \, yr^{-1}$ as function of redshift. The values are shown in Table 4. Our survey is sensitive to such objects at all redshifts (see next section, and Fig. 9), so this figure shows an unbiased and complete estimate of the cosmological evolution of the number density of the most luminous star forming galaxies in the Universe. It can be seen that, although such objects are largely confined to $z > 2$, their number density declines significantly beyond $z \approx 3.5$. Nevertheless, they still appear to persist at number densities significantly in excess of $10^{-6} \, Mpc^{-3}$ at $z \approx 5$.

7 STAR FORMATION RATES AND STELLAR MASSES

We estimated SFRs from the fits of the average submm galaxy template (Michałowski et al. 2010a, dust temperature $\sim 39$ K) to the $\geq 100$ $\mu$m photometry assuming either the optical redshift if available, or the long-wavelength redshift (Section 3). We integrated the template between 8 and 1100 $\mu$m and applied the Kennicutt (1998) conversion scaled to the Chabrier (2003) IMF: SFR $= 10^{-10} \times L_{IR}/L_\odot$. Our data sample the peak of the dust SED, so if we used a hotter SED template (Arp 220; Silva et al. 1998), then the obtained SFRs would be only $\sim 20$–30 per cent higher, within the systematic uncertainty of these estimates. For objects with optical counterparts we estimated stellar masses from the optical/near-IR SED fits (Section 6).

The resulting SFRs, stellar masses are given in Tables A7 and A8 in the appendix. The SFRs, stellar masses and sSFRs are shown as a function of redshift in Fig. 9. Table 9 shows median values of these estimates for sources at $z > 1$ (excluding discarded optical redshifts, see Section 6). Fig. 10 shows the SFRs as a function of stellar mass, in comparison with the main sequence of star-forming galaxies (Speagle et al. 2014).

The second panel of Fig. 10 shows that SCUBA-2 sources are very massive galaxies with median masses of $10^{11.15} \, M_\odot$. In this figure we also show our stellar mass sensitivity limit derived from the K-band detection limit (Table 1) k-corrected to the rest-frame K-band luminosity using the average submm galaxy template of Michałowski et al. (2010a) and using the mass-to-light ratio $M_{\text{star}}/L_K = 0.3 \, M_\odot/L_\odot^{-1}$. Most of the SCUBA-2 sources are above these limits by an order of magnitude, so our optical/near-IR data is deep enough to ensure the detection of the overwhelming majority of the optical/near-IR counterparts. Hence, our median mass estimate is not biased towards a high value, nor our sSFR estimate is biased towards a low value. These high stellar masses are not directly a result of high SFRs, because, in most cases, $\approx 90$ per cent of the stellar mass was formed before the currently observed star-formation activity (column 8 of Table 3). This is consistent with the findings of Dye et al. (2008) and Michałowski et al. (2010a, 2012a).

When modelled, as here, by a single burst, the mean age of earlier star formation is $\approx 1$–$1.5$ Gyr prior to the epoch of observation. However, we caution that this does not mean that the mass-dominant component was formed in an earlier even more violent short-lived starburst event. Instead, the $\sim 90$ per cent of the pre-existing mass could have formed in an extended (several Gyr) period, and indeed could have formed in smaller subcomponents, which subsequently merged.

The lower panels of Fig. 9 and Fig. 10 show that the SCUBA-2 sources at $z > 2$ (where most of them reside) are fully consistent with the main sequence of star-forming galaxies (as quantified by Speagle et al. 2014) and form its high-mass end. This is especially highlighted in the fourth panel of this figure, which limits the sample to those with $M_{\text{star}} > 10^{11} \, M_\odot$ and SFR $> 300 \, M_\odot \, yr^{-1}$, as our survey is sensitive to such objects even at $z \approx 5$. In this panel the medians of sSFRs in redshift bins are constant at $z = 1$–6 and, given the behaviour of the mean sSFR of other galaxies, SCUBA-2 sources stay on the main sequence above $z = 1.5$. This is also true for SCUBA-2 sources at $z > 4$. This is the first time that a significant sample of submm galaxies at such high redshifts has been studied in relation to the main sequence.

Even at $1 < z < 2$ most of the SCUBA-2 sources lie on or close to the main sequence, offset by less than a factor of 2. Only at $z < 1$ do the SCUBA-2 sources lie significantly more...
Figure 9. Star formation rates (SFR; first panel), stellar masses ($M_{\text{star}}$; second panel) and specific SFRs (third panel) of SCUBA-2 sources as a function of redshift. The last panel also shows the specific SFRs, but including only sources with $M_{\text{star}} > 10^{11} \, M_{\odot}$ and SFR > $300 \, M_{\odot} \, \text{yr}^{-1}$, as our survey is sensitive to such objects at all redshifts. Larger symbols correspond to sources with optical redshifts, whereas smaller symbols to those with only long-wavelength redshifts. The dotted line on the top panel shows the limit on $\text{SFR} = 1500 \, M_{\odot} \, \text{yr}^{-1}$ above which we do not detect any object. The solid lines on the second panel show the $3\sigma$ $M_{\text{star}}$ detection limit corresponding to the $K$-band flux limits from Table 1. The solid line in the two bottom panels represents the main sequence of star-forming galaxies, as measured by Speagle et al. (2014) plotted for $\log (M_{\text{star}}/M_{\odot}) = 11.2$. Light grey and dark grey regions represent the $2\sigma$ (0.4 dex) and $1\sigma$ (0.2 dex) scatter in this relation. Circles with error bars on these panels represent the median sSFRs for SCUBA-2 sources in the redshift bins indicated by the horizontal error bars. The apparent clumps in optical redshifts are due to photometric redshift focusing – the filters have a given width, so if a spectral feature happens inside one, then it tends to adopt the redshift placing this feature at a similar position with respect to the filter. However, the redshift errors and our adopted redshift bins are larger than this focusing, so this has no effect on our analysis.

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Figure 10. Star formation rates as a function of stellar mass for the SCUBA-2 sources in the COSMOS (circles) and UDS (squares) fields. The solid lines represent the main sequence of star-forming galaxies at various redshifts, as reported by Speagle et al. (2014). Most submm galaxies lie on the main sequence. Dots represent the synthetic main-sequence galaxies distributed according to the mass function of Ilbert et al. (2013) and Grazian et al. (2015) and the main sequence reported by Speagle et al. (2014), see Section 7. Their number above the submm galaxy SFR threshold (dashed line), corresponding to 3.5 mJy, is similar or larger than the number of real submm galaxies (corrected for completeness), which implies that submm galaxies can be fully explained as the most massive and most highly star-forming main-sequence galaxies, and hence they should not be regarded as a distinct starburst population. We note that the apparent asymmetry in the distribution of synthetic galaxies (enhancement above the main sequence) is an optical illusion. This can be verified by looking at a narrow mass range, which then shows a perfect symmetry.
above the main sequence, and correspond to starburst galaxies. At these redshifts our submm flux limit corresponds to a lower luminosity than that at higher redshifts, but the main-sequence normalisation declines even faster from $z \simeq 2$ to $z < 1$.

Finally, we note that, for sources that are in fact blends of several sources (Section 4), our SFRs are overestimated, as they include the contribution of other sources, whereas the stellar masses are correct, as long as we identify the correct main contributor to the submm flux. Hence, the
true sSFR for these sources are even lower, which makes our conclusion stronger that most of submm galaxies are not above the main sequence.

In order to test whether submm galaxies can indeed be almost exclusively main-sequence galaxies, we considered how many massive main-sequence galaxies with high SFRs are expected to be located in our \( \simeq 2.18 \, \text{deg}^2 \) fields, given what we know about the galaxy stellar mass function and SFRs of star-forming galaxies at a given redshift. To estimate the expected number density of such objects we used the mass function of Illert et al. (2013) at \( z < 4 \) and of Grazian et al. (2015) at \( z > 4 \). For each redshift bin shown in Fig. 10 we multiplied the integral of the corresponding mass function between \( \log(M_{\text{star}}/M_\odot) = 10-12 \) (the range spanned by submm galaxies) with the volume probed by our survey within this redshift bin to obtain the total number of star-forming galaxies in this mass range expected in our fields. Their masses were chosen randomly out of the mass function, so that the resulting mass distribution matches the measured mass function. To each of these synthetic galaxies we assigned an SFR based on the main sequence at that redshift (Speagle et al. 2014) and scattered them randomly by a number drawn from a Gaussian distribution with a standard deviation of 0.2 dex (the width of the main sequence, Speagle et al. 2014). These synthetic main-sequence galaxies are shown as dots in Fig. 10 and the number of them above the SFR cut corresponding to submm galaxies (dashed line) is shown on each panel as ‘Nsim’ (these most-star-forming synthetic galaxies are clearly marked as plus signs in Fig. 11).

Between \( z \simeq 1 \) and \( z \simeq 4 \) the number of predicted and observed bright submm galaxies is in very good agreement (to within a factor of 2) given the relative simplicity of this calculation. Indeed the predicted number is always larger that what is actually observed, particularly so at \( z > 4 \), and so given current data on the evolution of the galaxy mass function and the main sequence, there is clearly no problem explaining the prevalence of submm galaxies at all redshifts.

There are some obvious reasons that this calculation may overpredict somewhat the observed number of submm galaxies at the highest redshifts. Given the small number statistics at \( z > 4 \) redshift errors may be important, and in addition our completeness may be poorer than estimated. However, it is equally likely that the predicted number of massive star-forming galaxies may be in error at the highest redshifts, given our current limited knowledge of the form of the galaxy stellar mass function at \( z > 4 \) (the high-mass end being particularly vulnerable to systematic errors such as Eddington bias).

Nonetheless, these calculations, as illustrated in Fig. 11 and Fig. 12 clearly demonstrate that the observed properties of luminous high-redshift submm galaxies arise naturally from the evolving main sequence of normal star-forming objects, once the selection function inherent in submm surveys is taken into account.

8 DISCUSSION: EXTREME STAR FORMATION IN THE UNIVERSE

8.1 Main-sequence nature and the maximum SFR

Koprowski et al. (2016) showed that submm galaxies in deep SCUBA-2 fields are located on the main sequence, and now we have obtained a similar result for a brighter sample from shallower but larger fields. This is incompatible with the frequently assumed picture that submm galaxies are unusually powerful starbursts, significantly different from the general star-forming galaxy population. Instead, we have shown that submm surveys simply (and inevitably) select the most massive (and hence most star-forming) galaxies out of the main-sequence population. This suggests that most submm galaxies are not fuelled by extreme, transitory event such as a major merger (which would move them above the main sequence), but instead represent the final stages (shortly prior to quenching) of a long and (on average) fairly smooth, as-
cent up the main sequence. This interpretation is supported by recent simulations showing that all properties of submm galaxies can be explained by a sustained gas inflow, rather than by major mergers (Narayan et al. 2013).

It is clear however that some submm galaxies are powered by major mergers. CO and Hα observations revealed that in roughly half of the submm galaxies gas is distributed in multiple components and in the remaining half gas distribution is compact (Tacconi et al. 2008, Engel et al. 2011, Alaghband-Zadeh et al. 2012). This is consistent with a major merger scenario, but also with a clumpy disc scenario if the separation is not too large. On the other hand, near-IR (Targett et al. 2011, 2013, Wiklind et al. 2014, Chen et al. 2013), kinematic (Swinbank et al. 2011, Hodge et al. 2012, Menéndez-Delmestre et al. 2013) and resolved dust/gas studies (Bothwell et al. 2010, Hodge et al. 2012, 2013) of submm galaxies indeed reveals that some of them are large, clumpy disc galaxies, sometimes with potential merger signatures.

Due to our large and well-defined bright SCUBA-2 sample, this is the first time that it has proved possible to properly investigate the position of submm galaxies at $z > 4$ relative to the main sequence. As demonstrated in Figs 9 and 10 even at such high redshifts, submm galaxies are consistent on average with the main sequence. Hence, these galaxies represent the most powerful star-forming galaxies at these early epochs, but again are likely not powered by any unusual/extreme events.

It is instructive to investigate whether there is a limit to the SFR of submm galaxies. We have not detected any source above SFR $= 1500 \, M_\odot \, yr^{-1}$ (dotted line on the top panel of Fig. 9). This is because the sources in our sample do not exceed the $850 \, \mu$m flux of 17 mJy. This implies an upper limit on the number density of such extreme sources of $< 0.023 \, deg^{-2}$ (95 per cent confidence). This was calculated as 1/20 of a number density if there was one galaxy per 2.17 deg$^2$ field (the area of the combined UDS and COSMOS SCUBA-2 fields) and can be confirmed by generating random positions in a large area (e.g. 100 deg$^2$) and checking that, at this surface density, 95 per cent of random 2.17 deg$^2$ fields contain no sources. Sources more active than SFR $= 1500 \, M_\odot \, yr^{-1}$ have been confirmed in the past (Capak et al. 2004, 2011, Daddi et al. 2009b,Michałowski et al. 2010b, Ricchers et al. 2010, 2013, Horesh et al. 2013), but usually they were just single objects in given fields, so the estimate of their number density is difficult.

We note that our SFR cutoff value is higher than the maximum of $1000 \, M_\odot \, yr^{-1}$ proposed by Karim et al. (2013) based on the lack of $> 9$ mJy sources in the ALMA follow-up of LESS sources. However, their smaller parent single-dish sample contained only a few such sources, so the conclusion presented here is more robust. Indeed, $> 9$ mJy interferometric sources were detected by both the Submillimeter Array (SMA) (Younger et al. 2007, 2009, Barger et al. 2012) and ALMA (Simpson et al. 2015a). On the other hand Barger et al. (2014) found a turn-down in the SFR distribution function above $\sim 1100 \, M_\odot \, yr^{-1}$ (after the conversion to our adopted Chabrier (2003) IMF), which implies that such sources become increasingly rare, which is compatible with our cut-off value.
8.2 Submm galaxies without IDs

We have not found any IDs for around a third of SCUBA-2 sources (Table 2). They can be divided into three categories: (1) spurious or flux-boosted submm sources, (2) blends of several submm sources out of which none is bright enough for our ID method to work and (3) high redshift sources, with too low radio and mid-IR fluxes. Our ID method is likely to miss spurious sources (they would be very unlikely to yield IDs), and, as demonstrated in Fig. 2, would not identify many faint submm sources, especially at high redshift. Hence, our ID catalogue should reflect a relatively clean submm-flux-limited sample (removing problematic categories 1 and 2), but may underrepresent very high redshift sources, which are likely not to be IDed either. Indeed, the ID completeness of the entire sample (≈66 per cent) is lower than the ID completeness in the ALMA subsample (≈86 per cent). This is likely because the ALMA subsample is brighter (Fig. 2 of Simpson et al. 2015b), so it contains less spurious sources, for which our method would (correctly) return no ID.

We can estimate the fraction of sources in these categories based on our ID fraction (Table 2) and the ALMA training sample (Simpson et al. 2015b, and Section 3). In Section 3 we showed that for four out of 29 ALMA-observed SCUBA-2 sources our ID method misses dominant ALMA sources. One of them is not covered by the 24 μm imaging, but the lack of IDs for other three (≈10 per cent) indicates that they can be at very high redshifts. They are unlikely to be spurious sources, as the fluxes are confirmed by ALMA at the JCMT/SCUBA-2 resolution, then they are blended twice lower than measured, making it difficult to find IDs. Hence, sources with no IDs with z > 3 and z ∼ 4–8 mJy level. Two of them are not detected by Herschel implying a long-wavelength redshift of >3 and >4 (Section 3). The third has a significant Herschel signal, but there are two very strong 24 μm sources nearby complicating the photometry. In any case, some other SCUBA-2 sources with no IDs (for which we do not have ALMA data) may also belong to the high-z category. This can be tested by high-resolution submm interferometry and subsequent CO redshift search.

Some sources can be affected by blending. For three out of 29 ALMA-observed SCUBA-2 sources (≈10 per cent) the brightest ALMA component is fainter than half of the SCUBA-2 flux. Additionally, for two SCUBA-2 sources there are no ALMA counterparts. This means that for z ∼ 17 per cent of the SCUBA-2 sample the true submm flux may be twice lower than measured, making it difficult to find IDs. We also note that multiplicity should not influence our long-wavelength estimates, because if given sources are blended at the JCMT/SCUBA-2 resolution, then they are blended at the Herschel/SPIRE resolution. Hence, far-IR colours of the main contributor to the submm flux may be not significantly affected, unless the sources are at significantly different redshifts. Hence, sources with no IDs with zLW ∼ 2 are likely blends of galaxies at that redshift, whereas those with no IDs and zLW ≥ 4 are likely truly at these high redshifts, as blending should not result in an artificially high zLW.

8.3 Submm galaxies in cosmological context

Fig. 12 and Fig. 13 show the contribution of our submm galaxies to the cosmic SFR and stellar mass densities, respectively. The values are shown in Table 3. To calculate the volume of each redshift bin we assumed the combined area of the COSMOS and UDS SCUBA-2 imaging with 1.1 mm coverage of 1.15 deg². For each source we used our best redshift, either optical, or long-wavelength if optical was not available or rejected. Completeness corrections have been applied as described in Geach et al. (2017).

Bright submm galaxies, as studied here, contribute ≃ 2–4 per cent of the SFR density at z = 2–6, and ≃ 3 per cent to the stellar mass density at z = 2–4, rising to ≃ 10 per cent at z = 4–6. Deeper mm/submm surveys with SCUBA-2 (e.g. Casey et al. 2013 Barger et al. 2014 Copin et al. 2014 Bourne et al. 2017) and ALMA (Dunlop et al. 2017) show that fainter dusty star-forming galaxies contribute the vast majority of cosmic star formation rate density at z = 1–3.

Finally, in Fig. 14 and Table 4 we show the fraction of star-forming galaxies above log(M/M⊙) = 11 that are submm galaxies, calculated by dividing the number density of submm galaxies with log(M/M⊙) ≥ 11 in a given redshift bin by the integral of the mass function (Ilbert et al. 2013 Grazian et al. 2013 Caputi et al. 2013) above that mass. The power-law fit to this fraction results in the following dependence: (2.9 ± 0.4) × z^{1.5±0.2}. The fraction of submm galaxies increases with redshift and reaches ≃ 30 per cent at z = 4. This is because our selection function is nearly flat with redshift, whereas the normalisation of the main sequence is increasing, so the fraction of massive galaxies that should be detectable above our SFR-limited flux-density limit is expected to increase (albeit the total number density of such massive galaxies obviously rapidly declines with increasing redshift).

9 CONCLUSIONS

We have conducted an analysis of nearly 2000 submm sources detected in the ≃ 2 deg² 850-μm imaging of the COSMOS and UDS fields obtained with SCUBA-2 on the JCMT as part of the SCUBA-2 Cosmology Legacy Survey. This unique data set represents the largest homogeneous sample of 850-μm-selected sources assembled to date, and we have exploited this sample, along with the rich multiwave-length supporting data in these fields to shed new light on the physical properties and cosmological evolution of bright (S850 > 4 mJy) submm-selected galaxies.

We have completed the galaxy identification process for all 850-μm sources selected with S/N ≥ 3.5, but focus our scientific analysis on a high-quality subsample of 651 sources selected with S/N ≥ 4 and complete multiwave-length coverage extending to include 1.1-mm imaging. We have checked the reliability of our identifications, and the robustness of the SCUBA-2 fluxes, by revisiting the results of recent ALMA follow-up of a subset of the brightest sources in our sample. This shows that our identification method has a completeness of ≃ 86 per cent with a reliability of ≃ 92 per cent, and that only ≃ 15–20 per cent of sources are significantly affected by multiplicity. For completeness, we have also shown that the impact of source blending on the 850-μm source counts as determined with SCUBA-2 is modest; scaling the single-dish fluxes by ≃ 0.9 reproduces the ALMA source counts.

The optical/near-IR/mid-IR data, coupled at longer
wavelengths with the Herschel-SCUBA-2+AzTEC photometry, have enabled us to estimate the redshifts \((z)\) and star formation rates (SFR) of all sources in our entire sample, and stellar masses \((M_{\star,\text{est}})\) for the \(\simeq 75\) per cent of sources with optical/near-IR galaxy identifications.

For our \(4\sigma\) sample with 1.1 mm coverage we find median values of \(z = 2.40^{+0.10}_{-0.004}\) SFR = \(287 \pm 6\, M_{\odot}\ \text{yr}^{-1}\) and \(\log(M_{\star,\text{est}}/M_{\odot}) = 11.12 \pm 0.02\) (the latter for 349/651 sources with optical identifications), and we have shown that these properties clearly locate bright submm galaxies on the high-mass end of the ‘main sequence’ of star-forming galaxies out to \(z \simeq 6\), suggesting that major mergers are not a dominant driver of the high-redshift submm-selected population. We have also shown that the number densities of these high-mass main-sequence galaxies are consistent with recent determinations of the evolving galaxy stellar mass function, and have calculated the contributions of these most luminous star-forming main-sequence galaxies to cosmic star formation rate density and cosmic stellar mass density as a function of redshift.

We conclude that the submm galaxy population is essentially as expected (both in terms of evolving comoving number density, and with regard to inferred physical properties), albeit reproducing the evolution of the main sequence of star-forming galaxies remains a challenge for theoretical models/simulations.

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This study was based in part on observations obtained with MegaPrime/MegaCam, a joint project of CFHT and CEA/DAPNIA, at the Canada-France-Hawaii Telescope (CFHT) which is operated by the National Research Council (NRC) of Canada, the Institut National des Science de l'Univers of the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawaii. This work is based in part on data products produced at TERAPIX and the Canadian Astronomy Data Centre as part of the Canada-France-Hawaii Telescope Legacy Survey, a collaborative project of NRC and CNRS.

The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

This research has made use of data from HerMES project [http://hermes.sussex.ac.uk/]. HerMES is a Herschel Key Programme utilising Guaranteed Time from the SPIRE instrument team, ESAC scientists and a mission scientist. The HerMES data was accessed through the Herschel Database in Marseille (HeDaM [http://hedam.lam.fr]) operated by CoSAM and hosted by the Laboratoire d’Astrophysique de Marseille. PACS has been developed by a consortium of institutes led by MPE (Germany) and including UVIE (Austria); KU Leuven, CSL, IMEC (Belgium); CEA, LAM (France); MPIA (Germany); INAF-IASF/OAA/OAP/OAT; LENS, SSSA (Italy); IAC (Spain). This development has been supported by the funding agencies BMVIT (Austria), ESA-PRODEX (Belgium), CEA/CNES (France), DLR (Germany), ASI/INAF (Italy), and CICYT/MCYT (Spain). SPIRE has been developed by a consortium of institutes led by Cardiff University (UK) and including Univ. Lethbridge (Canada); NAOC (China); CEA, LAM (France); IFSI/IFAF/OAP/OAT; LENS, SSSA (Italy); IAC (Spain); Stockholm Observatory (Sweden); Imperial College London, RAL, UCL-MSL, UKATC, Univ. Sussex (UK); and Caltech, JPL, NHSC, Univ. Colorado (USA).

This development has been supported by national funding agencies: CSA (Canada); NAOC (China); CEA, CNES, CNRS (France); ASI (Italy); MCINN (Spain); SNSB (Sweden); STFC (UK); and NASA (USA).

This work is based on observations taken by the 3D-HST Treasury Program (GO 12177 and 12328) with the NASA/ESA HST, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Based on data obtained with the European Southern Observatory Very Large Telescope, Paranal, Chile, under Large Program 185.A-0791, and made available by the VUDS team at the CESAM data center, Laboratoire d’Astrophysique de Marseille, France. The HST data matched to the VUDS-DR1 are described in [Groggin et al. 2011] and [Koekemoer et al. 2011] for CANDELS and include data from the ERS [Windhorst et al. 2011]. This paper uses data from the VIMOS Public Extragalactic Redshift Survey (VIPERS). VIPERS has been performed using the ESO Very Large Telescope, under the “Large Programme” 182.A-0886. The participating institutions and funding agencies are listed at [http://vipers.inaf.it]. Based on zCOSMOS observations carried out using the Very Large Telescope at the ESO Paranal Observatory under Programme ID: LP175.A-0839.

This research has made use of the Tool for Operations on Catalogues And Tables (TOPCAT; Taylor 2005; www.starlink.ac.uk/topcat/), SAOImage DS9, developed by Smithsonian Astrophysical Observatory (Joy & Mandel 2003); SExtractor: Software for source
REFERENCES

Watson D., Christensen L., Knudsen K.K., Richard J., Gallazzi A., Michałowski M.J., 2015, Nat, 519, 327

APPENDIX A: ONLINE TABLES
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Table A1: Radio, 24 µm and 8 µm identifications of the JCMT/SCUBA2 objects in the COSMOS field. This table is available in its entirety in the online version.
Table A5: Optical fluxes of the JCMT/SCUBA2 objects in the COSMOS field. This table is available in its entirety in the online version.

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Table A6: Optical fluxes of the JCMT/SCUBA2 objects in the UDS field. This table is available in its entirety in the online version.

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Table A7: Redshift and physical properties of the JCMT/SCUBA2 objects in the COSMOS field. This table is available in its entirety in the online version.

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Table A8: Redshift and physical properties of the JCMT/SCUBA2 objects in the UDS field. This table is available in its entirety in the online version.

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