Deep sub-mm surveys with SCUBA

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Abstract. We review published deep surveys in the submillimeter (sub-mm) regime from the new Sub-millimetre Common User Bolometer Array (SCUBA, [1]) on the 15-m James Clerk Maxwell Telescope (JCMT), Mauna Kea, Hawaii. Summarising the number counts of faint sub-mm sources determined from the different surveys we show that the deepest counts from our completed SCUBA Lens Survey, down to 0.5 mJy at 850 µm, fully account for the far-infrared background (FIRB) detected by COBE. We conclude that a population of distant, dust-enshrouded ultraluminous infrared galaxies dominate the FIRB emission around 1 mm. We go on to discuss the nature of this population, starting with the identification of their optical counterparts, where we highlight the important role of deep VLA radio observations in this process. Taking advantage of the extensive archival Hubble Space Telescope (HST) observations of our fields, we then investigate the morphological nature of the sub-mm galaxy population and show that a large fraction exhibit disturbed or interacting morphologies. By employing existing broadband photometry, we derive crude redshift limits for a complete sample of faint sub-mm galaxies indicating that the majority lie at $z < 5$, with at most 20% at higher redshifts. We compare these limits to the initial spectroscopic results from various sub-mm samples. Finally we discuss the nature of the sub-mm population, its relationship to other classes of high-redshift galaxies and its future role in our understanding of the formation of massive galaxies.

Introduction

The extragalactic background light is the repository for all emission from the distant Universe and thus contains unique information about the star-formation history of the Universe. The far-infrared component of this (the FIRB) was detected by COBE (e.g. [2]) at a level comparable to that seen in the optical background [3], suggesting that a large proportion of the stars seen in the local Universe were formed in dust-obscured galaxies at high redshifts [4]. Such strongly star-forming, dusty, distant galaxies would be luminous sub-mm sources, due to the re-radiation in the rest-frame sub-mm of the UV/optical starlight absorbed by the dust. Thus deep sub-mm observations, at $\lambda \gtrsim 100 \mu m$, would be a fruitful avenue to pursue in the search for these forming galaxies. The strong negative K-corrections provided by the thermal dust spectrum of galaxies also means these systems are easily observable.
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out to high redshift [5]. A doppelgänger for Arp 220, with an star-formation rate (SFR) of \( \gtrsim 100 \, M_\odot \, \text{yr}^{-1} \), would have a 850-\( \mu \)m flux density of \( \gtrsim 3 \, \text{mJy} \) out to \( z \sim 10 \) (\( \gtrsim 0.3 \, \text{mJy} \) for \( q_o = 0.05 \) [5]). The recently commissioned SCUBA camera on JCMT can achieve this flux limit across a 5 sq. arcmin field in one night.

Faint Galaxy Counts in the Sub-mm

At the time of writing, 850-\( \mu \)m counts of faint extragalactic sources have been published by four groups [6–9]. The first indications of the surface density of mJy 850-\( \mu \)m galaxies was given by Smail, Ivison & Blain [6], who took advantage of gravitational amplification by massive cluster lenses to increase the sensitivity of their SCUBA maps, and derived a source count of \((2.5 \pm 1.4) \times 10^3 \, \text{deg}^{-2}\) down to a flux density limit of 4 mJy on the basis of 6 detections. This surface density has been broadly confirmed by a number of subsequent studies of blank fields, which spurn lens amplification, preferring simple brute-force integration to obtain the necessary sensitivity.\(^2\) These studies include maps of the Canada-France Redshift Survey fields (CFRS, [9]), the Lockman Hole and Hawaii Survey Fields [8] and the Hubble Deep Field [7], and detect 11, 2 and 5 sources above their respective flux limits. The latter two surveys reach the blank-field confusion limit of the JCMT [10] in their deepest integrations. The sub-mm source densities derived from the different surveys are plotted in Fig. 1 to show the broad level of agreement reached.

The latest results from the analysis of the completed SCUBA Lens Survey [12] are also shown in Fig. 1. The complete sample comprises a total of 17 galaxies detected at 3\( \sigma \) significance or above, and 10 detected above 4\( \sigma \), in the fields of seven massive and well-studied cluster lenses at \( z = 0.19–0.41 \). The total surveyed area is 0.01 degree\(^2\), with a sensitivity of better than 2 mJy in the image planes. The analysis of these catalogues [13] makes use of well-constrained lens models for all the clusters (e.g. [14]) to accurately correct the observed source fluxes for lens amplification. For the median source amplification, \( \sim 2.5 \times \), our survey covers an area of the source plane equivalent to roughly three times the SCUBA HDF map at a comparable sensitivity and with a factor of two finer beam size. At higher amplifications, the survey covers a smaller region, but at a correspondingly higher sensitivity (e.g. \( \sim 1 \, \text{sq. arcmin at } \sigma_{850} \sim 0.1 \, \text{mJy} \)) and resolution. The uncertainties associated with our lensing analysis are included in the final error quoted on the derived counts. The total uncertainty in the lensing correction is at most comparable to the typical error in the absolute SCUBA calibration. The magnification produced by the massive cluster lenses allows us to constrain the source counts down to 0.5 mJy [13], four times fainter than the deepest blank-field counts published. Moreover, these observations are less affected by confusion noise, due to the expanded view of the background source plane provided by the cluster

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1) We assume \( q_o = 0.5 \) and \( h_{100} = 0.5 \) throughout.

2) Several other groups are pursuing surveys of lensing clusters using SCUBA, including those headed by Scott Chapman and Paul van der Werf, first results from these should appear soon.
At 450 $\mu$m, which SCUBA provides simultaneously with the 850-$\mu$m maps, only a few sources have been detected in any of the published surveys. This is due to a combination of the lower atmospheric transmission at 450 $\mu$m in normal conditions on Mauna Kea, the lower efficiency of the JCMT dish surface at 450 $\mu$m and the relatively high redshifts of the bulk of the sub-mm population [7].

The cumulative 850-$\mu$m counts of Smail, Ivison & Blain (1997) accounted for roughly 30% of the FIRB detected by COBE (e.g. [2,15]). The counts from the HDF brighter than the confusion limit at 2 mJy account for close to 50% of the FIRB, while the deepest counts from the lens fields [13] indicate that the bulk of the FIRB is resolved at 0.5 mJy. This suggests that not only must the counts converge around 0.5 mJy, but that the FIRB is dominated by emission from the most luminous sources. This is a remarkable achievement given that the FIRB was detected only three years ago and SCUBA has been operating for a little over a year.
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Having resolved the background we can now study the nature of the populations contributing to the FIRB and so determine at what epoch the background was emitted. Here again our survey has the advantage of lens amplification, this time in the optical and near-IR where the identification and spectroscopic follow-up are undertaken. Typically the counterparts of our sub-mm sources will appear $\sim 1$ magnitude brighter than the equivalent galaxy in a blank field.

![Figure 2](image.png)

**FIGURE 2.** The SCUBA 850-$\mu$m map of the rich cluster A1835 ($z = 0.25$), this is overlayed on a deep $I$-band image of the cluster taken with the Palomar 5.1-m Hale. Two bright sub-mm sources are visible either side of the central cluster galaxy, both are coincident with $> 100$-$\mu$Jy radio sources in our deep VLA map [17]. The eastern source is identified with an $I \sim 21$ interacting galaxy at $z = 2.6$ [16,17], while the western source has no obvious counterpart at the position of the sub-mm/radio peak. Weak sub-mm emission is also detected from vigorous star formation in the central galaxy of this cooling-flow cluster [18].

**Identifications and Morphologies of SCUBA Galaxies**

The sub-mm fluxes of the sources detected in all the published surveys are in the range $S_{850} \sim 0.5$–10 mJy, equivalent to luminosities of $\log_{10} L_{\text{FIR}} \sim 12$–13 if they lie at $z \gtrsim 1$, and so they class as ultraluminous infrared galaxies (ULIRGs). Smail et al. (1998, [12]) presented optical identifications obtained from deep HST
and ground-based images for galaxies selected from the SCUBA Lens survey (e.g. Fig. 2). Down to a limit of $I \sim 25$, counterparts are identified for 14 of the 16 sources in the SCUBA Len s survey and for 9/10 sources in the SCUBA catalog that lie within the optical fields. This rate of optical identification, 80–90%, down to $I \sim 25$ is similar to that achieved by the other sub-mm surveys [7,9]. The bulk of these sources are resolved in the optical images indicating that they are galaxies.

We are undertaking near-IR imaging of all our fields to search for any extremely red counterparts which could have been missed in the optical identifications. A link has been suggested between the population of extremely red objects (EROs) and the sub-mm galaxies due to the recent sub-mm detection of one of the most well-studied EROs, HR10 [19]. We have so far identified only one possible ERO counterpart to a sub-mm source in our survey with the bulk of the sub-mm galaxies showing optical–near-IR colors more typical of the general field, $(I - K) \sim 2-4$.

We are using ultra-deep 1.4-GHz VLA maps to confirm the reliability of the identifications [20] and find radio counterparts brighter than $\sim 50 \mu$Jy (equivalent to intrinsic flux densities of $\gtrsim 20 \mu$Jy) for over 60% of the sub-mm sources. Again this success rate is similar to that found for sub-mm/radio comparisons in the HDF [21]. The radio fluxes of the SCUBA sources are broadly in line with those expected if the sub-mm emission is powered by starbursts and the sources follow the locally determined $L_{\text{FIR}} - L_{\text{5GHz}}$ correlation for galaxies. Similar analysis of the other surveys await deep radio observations and confirmation of the astrometric accuracy of the SCUBA maps.

The morphologies of those galaxies for which we have high-resolution optical imaging fall into three broad categories: faint disturbed galaxies and interactions; faint galaxies too compact to classify reliably; and dusty, star-forming galaxies at intermediate redshifts [12,22]. We show in Fig. 3 the $R$- or $I$-band images of the optically faint sub-mm galaxies, these illustrate the dominance of disturbed morphologies in this sample. About 70% of the faint galaxies are disturbed or interacting, suggesting that in the distant Universe, as in the local one, interactions remain an important mechanism for triggering starbursts and for the formation of ULIRGs [12]. The faint, compact galaxies may represent a later evolutionary stage of these mergers, or more centrally concentrated starbursts. It is likely that some of these will also host active galactic nuclei.

The Redshift Distribution of Faint Sub-mm Galaxies

An analysis of the optical colors of our sub-mm sample to search for the signature of the Lyman break in bluer passbands allows us to estimate a crude redshift distribution from their identification in deep $B$- and $V$-band images [12]. This indicates that $\gtrsim 75\%$ of the optically-identified galaxies have $z \lesssim 5.5$ whilst $\gtrsim 50\%$ lie at $z \lesssim 4.5$ on the basis of $B$-band identifications alone. Photometric redshifts have been used in the HDF [7] and CFRS [22] to place limits on the redshift distributions of sub-mm galaxies in these samples, the estimated redshifts span $z \sim 1-4$. Although the reliability of the photometric redshifts obtained for such
dusty systems has yet to be tested, these results are consistent with the limits above. We conclude that the luminous sub-mm population is broadly coeval with the more modestly star-forming galaxies selected by UV/optical surveys of the distant Universe (e.g. [23]). However, the individual SCUBA galaxies have SFRs which are typically an order of magnitude higher than those of the optically selected galaxies, as well as being apparently more dust (and hence metal?) rich.

A further attraction of using lenses in our survey was the possibility of deriving redshift estimates for galaxies too faint for spectroscopic identification. Using our detailed mass models, redshifts can be determined for any background galaxy whose distortion can be measured from our HST imaging, using the relationship between source redshift and apparent shear for the lens model [24], a technique whose accuracy has been recently confirmed [25]. In this way we have estimated a redshift of \( z = 1.6 \pm 0.2 \) for an arclet detected in our survey with an intrinsic apparent magnitude of \( I = 25.3 \).

Preliminary results from spectroscopic surveys of the different sub-mm samples

FIGURE 3. The 12 optically-faint sub-mm galaxies from the SCUBA Lens Survey sample for which we have high-resolution \( R \)- or \( I \)-band imaging [12]. Each panel is \( 10 \times 10 \) arcsec corresponding to \( \gtrsim 80 \) kpc at \( z > 1 \) and they are ordered from the upper-left on the basis of their morphologies: 6 disturbed/interacting, 4 compact/featureless (including a strongly-distorted arclet) and 2 blank fields. The images are centred on the most likely optical candidate where one is known. The centroids of the sub-mm sources are indicated by crosses. Note that these images span a range in exposure times and resolutions [12].
are beginning to appear, although none are yet complete. First indications from the existing CFRS redshift survey [22], for which the majority of galaxies have \( z < 0.8 \), unsurprisingly finds a low redshift for the identified sources, \( z \sim 0.1–0.7 \). Spectroscopic observations of the SCUBA Lens Survey sample with Keck, CFHT and WHT have identified a number of distant galaxies in the range \( z \sim 1–3 \) [16] as well as several galaxies at \( z \sim 0.2–0.4 \) in the foreground cluster lenses [16,18]. These sources are removed from our count analysis, but their detection does confirm that SCUBA has the ability to routinely detect star-forming galaxies at \( z < 1 \) [22]. The more distant systems include a \( z = 2.8 \) dusty AGN/starburst [26] and a \( z = 2.6 \) starburst [16,17]. These spectroscopic observations support the photometrically-derived redshift limits for the bulk of the population as well as giving more information about the dominant emission processes in individual galaxies. In particular, the spectra provide some indication of the relative fractions of AGN and starbursts in the sub-mm population. Nevertheless, the spectroscopic surveys currently have nothing to say about the 10–20% of SCUBA sources that have no obvious optical counterpart. Owing to the large negative \( K \)-correction in the sub-mm, these sources may be at \( z > 5 \), and thus are the most interesting sources to followup.

**FIGURE 4.** The spectral energy distribution (SED) of SMM J02399−0136 at \( z = 2.8 \), adapted from [26]. The intrinsic FIR luminosity of this source is \( 10^{13} \, L_{\odot} \), after correction for lens amplification using our lens model, making it one of the most luminous galaxies known. The strong peak around 100\( \mu \)m in the restframe, probed by the SCUBA observations at 450\( \mu \)m–2 mm, is emission from dust at 40–50 K in the galaxy. The radio emission from this galaxy is at a level expected from the high SFR, as shown by the agreement with the rescaled composite SED of luminous *IRAS* galaxies plotted here [27].
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The Physical Properties of Sub-mm Galaxies

Further insights into the nature of the sub-mm-selected galaxies come from detailed investigations of the physical properties of this population (e.g. SFR, $T_{\text{dust}}$, $M_{\text{dust}}$, $M_{\text{gas}}$, etc.). These studies are not easy though, in particular turning the observed sub-mm flux into a SFR or dust mass requires a number of uncertain steps, even in the absence of competing contributions from an AGN and a starburst within a single galaxy. The basis for all of these analyses are multi-wavelength observations, especially in the sub-mm. Fortunately the 450/850-µm arrays and 1.3- and 2.0-mm single-channel bolometers on SCUBA can provide the necessary sub-mm data to constrain quantities such as the dust temperature in high-redshift galaxies. Radio observations are useful not only to provide more accurate positions, but also to rule out non-thermal contributions to the sub-mm flux.

A well-sampled SED is shown in Fig. 4 for the brightest source in the SCUBA Lens Survey, SMM J02399−0136 at $z = 2.8$ [26]. The amplification-corrected FIR luminosity of this galaxy is $10^{13} \, L_\odot$, its dust temperature is $T_{\text{dust}} = 40-50 \, \text{K}$ and the dust mass is around $M_{\text{dust}} \sim 6 \times 10^8 \, M_\odot$. The estimated SFR for this galaxy is $\gtrsim 2000 \, M_\odot \, \text{yr}^{-1}$, although the optical spectrum indicates that it hosts a Seyfert-2 nucleus, suggesting that some fraction of the $L_{\text{FIR}}$ is probably attributed to the AGN [26]. SMM J02399−0136 has recently been detected in CO using the Owens Valley Millimeter Array [28], revealing the presence of $\sim 2 \times 10^{11} \, M_\odot$ of molecular gas, a dynamically important component of this massive galaxy and an enormous reservoir of fuel to power the star-formation. At this time, SMM J02399−0136 is the only sub-mm-selected galaxy for which such detailed observations are available.

The Nature of the Faint Sub-mm Population

We are beginning to build up a picture of the population of distant, luminous sub-mm galaxies which dominate the FIRB at wavelengths around 1 mm. The fact that the sub-mm population detected by SCUBA can account for all of the COBE background indicates that a substantial fraction (up to half) of the stars in the local Universe could be formed in these systems. The properties of this population are similar to those of ULIRGs in the local Universe, with the important distinction that they contribute a sub-mm luminosity density at early epochs that is more than an order of magnitude greater than the corresponding galaxies today. Detailed observations of this population can be used to trace the amount of high-redshift star-formation activity that is obscured from view in the optical by dust, and so is missing from existing inventories of star-formation activity in the distant Universe [6,7]. In this way a more complete and robust history of star formation for the Universe can be constructed.

As with local ULIRGs, there is uncertainty over the exact contributions from AGN and starbursts to this luminosity density. Insight may come through searches for hard X-ray emission from the sub-mm galaxies using AXAF, as these should detect all but the most heavily enshrouded AGN at $z > 1$ [29]. These searches will
also provide an estimate of the total contribution from the dust-obscured AGN to the X-ray background [29,30]. At the current time we can only state that \( \gtrsim 20\% \) of the sub-mm population shows obvious spectral signatures of an AGN — although this does not mean that the AGN dominates the emission in the sub-mm. Assuming that the bulk of the sub-mm emission arises from starbursts, we find that the total amount of energy emitted by dusty galaxies is about four times greater than that inferred from rest-frame UV observations, and that a larger fraction of this energy is emitted at high redshifts [4]. The simplest explanation for these results is that a large population of luminous strongly obscured galaxies at redshifts of \( z \lesssim 5 \) is missing from optical surveys of the distant Universe.

Finally, we come to the question of what class of object the sub-mm galaxies will evolve into by the present day? The similarities of these sources to local ULIRGs, which are expected to evolve into elliptical galaxies [31], along with their apparently high SFRs, which if sustained over \( \sim 1 \) Gyr would form an entire \( L^* \) galaxy at high redshift, suggest that the sub-mm population may be young, massive elliptical galaxies [6,9]. A question then arises concerning the relationship between the sub-mm population and the other class of high-redshift source which has been identified with forming ellipticals: the Lyman-break galaxies [32]. These objects appear to have typically lower SFRs and less dust than the sub-mm galaxies. The two populations could be naturally linked if the dust content of young galaxies is coupled to their masses or luminosities [33], such that the more massive galaxies are dustier. This behaviour would parallel the metallicity relation for elliptical galaxies, which show increasing metal enrichment with increasing galaxy mass, arising from the retention of processed gas by the potentials of the more massive galaxies. We would therefore identify the most massive, young ellipticals with the sub-mm galaxies and the less massive ellipticals and bulges with the Lyman-break objects. Thus detailed observations of the sub-mm population should give much needed observational information for models of the formation and evolution of massive galaxies [4]. In particular we look forward to further CO detections of sub-mm galaxies with both the existing and next-generation millimeter arrays to study the kinematics of these systems and hence determine their masses.

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