Submm Continuum Surveys for Obscured Galaxies

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**Abstract.** We discuss deep surveys in the submm regime using the SCUBA bolometer array on the JCMT. At 850µm SCUBA has resolved the bulk of the submm background (SMBR) detected by COBE into discrete sources brighter than 0.5mJy. The on-going identification and characterisation of this population at other wavelengths suggests that the bulk of the submm sources brighter than \(\sim 1\) mJy lie at \(z > 1\), with a median redshift for the population of \(< z > \sim 2–3\). The optical/near-infrared properties of the counterparts to the submm sources breakdown as follows: roughly two-thirds have reliable identifications with the others being more ambiguous. Of those with identifications about half are optically bright \(I < 23\) mergers or interactions with a high proportion showing signatures of AGN activity and the other half are optically faint \(I > 25\) including both blank fields and Extremely Red Objects (EROs). We conclude that a population of distant, highly obscured ultraluminous infrared galaxies (ULIRGs) dominates the SMBR. The wide range in the characteristics of the optical counterparts is consistent with the dispersion in the restframe UV properties of local ULIRGs. We suggest that the faint submm population comprises a class of high redshift dusty, mergers associated with the formation of present day luminous elliptical galaxies.
1. Introduction

The energy density in the extragalactic background radiation at optical/UV wavelengths is roughly equal to that seen in the far-infrared/submm (e.g. Bernstein et al. 1999; Puget et al. 1996; Fixsen et al. 1998). The simplest interpretation of this observation (ignoring contributions from dust-enshrouded AGN) is that averaged over all epochs, around half of all the star formation in the Universe has occurred in highly obscured regions. Clearly if we wish to obtain a complete and unbiased view of the star formation history of the Universe, necessary to constrain models of galaxy formation and evolution (Baugh et al. 1998), we need to understand in detail what fraction of star formation is obscured by dust and how this varies with epoch and environment. To achieve this we must investigate the nature and origin of the far-infrared/submm background and that requires the resolution of the background into discrete sources and the study of their individual and collective properties.

This review begins by discussing observational programmes in the submm with the Sub-millimeter Common User Bolometer Array (SCUBA, Holland et al. 1999) on the 15-m JCMT which have achieved the aim of resolving the bulk of the extragalactic background at 850 µm into discrete sources. We then discuss follow-up observations of these sources and use these to explore the broad characteristics of the populations contributing to the submm background.

As a benchmark for the following discussion we note that a ULIRG similar to Arp 220 with a far-infrared luminosity of \( L_{\text{FIR}} \sim 3 \times 10^{12} L_\odot \) and a star-formation rate (SFR) of \( \sim 300 M_\odot \text{yr}^{-1} \) would have a 850-µm flux density of \( \gtrsim 3 \text{mJy} \) out to \( z \sim 10 \) in a spatially flat Universe and \( \gtrsim 0.3 \text{mJy} \) for an open Universe with \( q_0 = 0.05 \) (Hughes & Dunlop 1997). In two nights of observing in good conditions with SCUBA it is possible achieve a 3σ flux limit of 3 mJy across a 160''-diameter field, probing a volume of 10⁶ Mpc³ out to \( z \sim 10 \) for dusty galaxies as luminous as Arp 220.

2. The Number Counts of the Faint Submm Population

The advent of sensitive submm imaging with SCUBA has allowed a number of groups to undertake ‘blind’ surveys for faint submm galaxies. Results on the number density of sources in blank fields as a function of limiting 850-µm flux density have been published by three groups: Hughes et al. (1998) worked with a single deep map centered on the Hubble Deep Field (HDF); while Barger et al. (1998, 1999b) employed a combination of deep/narrow and wide/shallow observations of fields in the Lockman Hole and Hawaii Survey Field regions, finally there is a on-going survey of areas included in the Canada-France Redshift Survey (first results given in Eales et al. 1999). The surface densities of sources measured by the different groups are shown in Fig. 1. Due to the modest resolution of these maps, 15'' FWHM, they are confusion limited at \( \sim 2 \text{mJy} \).

Our collaboration has taken a complimentary approach to these ‘blank’ field surveys by using massive gravitational cluster lenses to increase the sensitivity

\[ \text{We assume } q_0 = 0.5 \text{ and } h_{100} = 0.5 \text{ unless otherwise stated. In addition, unless identified as 'observed', all magnitudes/fluxes are corrected for lens amplification.} \]
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Figure 1. The cumulative 850-µm counts from published SCUBA surveys. The latest counts from the Blain et al. (1999a) analysis of the SCUBA Cluster Lens Survey are marked by solid circles. Counts from Barger et al. (1998; B98, 1999b; B99), Eales et al. (1999; E99), Holland et al. (1998, H98) Hughes et al. (1998; HDF) and Smail, Ivison & Blain (1997; S97) are also shown. P(D) indicates the limit from Hughes et al.'s confusion analysis in the HDF. The solid line shows a crude parameterisation of the counts, $N(> S) = 7.9 \times 10^3 S^{-1.1}$, while the counts from a non-evolving model based on the local IRAS 60-µm luminosity function are given by the dotted.

and resolution of SCUBA. The first deep submm counts were based on maps of two clusters (Smail, Ivison & Blain 1997) and the survey was subsequently expanded to cover seven lensing clusters at $z = 0.19–0.41$ (Smail et al. 1998; Blain et al. 1999a). The complete sample comprises a total of 17 galaxies detected at $3 \sigma$ significance or above, with 10 detected above $4 \sigma$, from a total surveyed area of $\sim 40$ sq. arcmin in the image plane down to a $1 \sigma$ flux limit of $\sim 1.5$ mJy at 850 µm. Two of these sources are identified with the central cluster galaxies in the clusters A 1835 and A 2390 and as such are removed from our analysis, although see Edge et al. (1999) for more discussion of these systems. The analysis of our catalog makes use of well-constrained lens models for all the clusters to accurately correct the observed source fluxes for lens amplification (Blain et al. 1999a). For the median source amplification, $\sim 2.5 \times$, our survey covers an area of the source plane equivalent to $15$ sq. arcmin to a $3 \sigma$ flux limit of $\sim 2$ mJy. The lens amplification also results in a factor of two finer beam size at this depth so that these counts have a fainter confusion limit than the blank field observations. At higher amplifications, the survey covers a smaller region, but at a correspondingly higher sensitivity (e.g. $\sim 1$ sq. arcmin at $\sigma_{850} \sim 0.1$ mJy) and resolution. The uncertainties associated with our lensing analysis are included in the final error quoted on the derived counts (Blain et al. 1999a). The total uncertainty in the lensing correction is at most comparable to the typical error in the absolute SCUBA calibration.

The 850-µm counts from the analysis of Blain et al. (1999a) are shown in Fig. 1 and are in agreement with the results from the other surveys at $\geq 2$ mJy. However, the magnification produced by the massive cluster lenses allows us to
also constrain the source counts down to 0.5 mJy, four times fainter than the deepest blank-field counts published and free from confusion noise.

The cumulative 850-µm counts down to 4 mJy from Smail, Ivison & Blain (1997) accounted for roughly 30% of the SMBR detected by COBE (e.g. Puget et al. 1996; Fixsen et al. 1998). The counts from later surveys down to the blank field confusion limit of JCMT at 2 mJy account for close to 50% of the SMBR, while the deepest counts from the lens fields indicate that the bulk of the SMBR is resolved by 0.5 mJy (Blain et al. 1999a). The majority of the SMBR is thus produced by sources with 850-µm fluxes of 1–10 mJy and as we discuss in the next section these galaxies are likely to lie at \( z \gtrsim 1 \) and hence they have intrinsic bolometric luminosities of \( 10^{12}–10^{13}L_{\odot} \) and densities of around \( 10^{-5}\text{Mpc}^{-3} \).

In addition to the 850-µm maps discussed above, SCUBA also provides simultaneous 450-µm imaging of the same fields. However, the combination of modest atmospheric transmission at 450 µm in normal conditions on Mauna Kea and the lower efficiency of the JCMT dish surface at shorter wavelengths has restricted the results appearing in this waveband. Based upon a similar analysis to Blain et al. (1999a), using those 450-µm maps from the lens survey where useful sensitivity was obtained we derive an approximate cumulative source density of 1000 deg\(^{-2}\) brighter than 20 mJy at 450 µm. This surface density is consistent with the number of 450-µm detections in the Eales et al. (1999) survey and the reported lack of detections in the HDF by Hughes et al. (1998). As we discuss in the next section the relative paucity of 450-µm sources suggests a fairly high redshift for the bulk of the submm population, \( z \gg 1 \).

Having resolved the background we can now study the nature of the populations contributing to the SMBR and so determine at what epoch the background was emitted. Here again our survey has the advantage of lens amplification, this time in the radio and optical/near-IR where the identification and spectroscopic follow-up are undertaken. Typically the counterparts of our submm sources will appear \( \sim 1 \) magnitude brighter than the equivalent galaxy in a blank field.

3. The Redshift Distribution of the Faint Submm Population

Photometric techniques for estimating the redshifts of candidate counterparts to submm sources have been employed by Hughes et al. (1998) and Lilly et al. (1999) leading to the suggestion that the bulk of the population lay at \( z = 2–4 \) or \( z = 0.1–3 \) respectively. However, these analyses are based upon the spectral energy distributions (SED) of local optically-selected galaxies and the diversity of the restframe UV/optical properties of local ULIRGs (Trentham et al. 1999) and their differences from ‘normal’ galaxies suggests that such analyses are fraught with complications. More general constraints on the maximum possible redshift of the submm population come from the search for the signature of Lyman-α absorption due to the intergalactic medium in the broad-band photometry of candidate counterparts (Smail et al. 1998). The detection of the bulk of the proposed counterparts in our survey in \( B \) or \( V \) imaging indicated that at least three-quarters were at \( z \lesssim 5.5 \) and more than half were likely to have \( z \lesssim 4.5 \). While admittedly weak, these constraints are free from concerns over the SEDs adopted for the distant ULIRGs and suggest that proportion of the faint submm population at very high redshifts, \( z > 5 \), is small (see Eales et al. 1999).
The cumulative redshift distribution for the SCUBA lens survey. We have used the spectroscopic redshifts of those galaxies known to be reliable counterparts from Barger et al. (1999a) and combined these with the probable redshift ranges of the remaining sources derived from their observed $\alpha_{1.4}^{850}$ indices or limits. The solid line shows the cumulative distribution if we assume a flat probability distribution for the sources within their allowed $z_\alpha$ ranges from the Carilli & Yun (1999) models and a maximum redshift of $z = 8$ for those sources where the $\alpha_{1.4}^{850}$ indices only provide a lower redshift limit. In contrast, the dashed line gives the conservative redshift distribution which is obtained if all sources are assumed to lie at their lower $z_\alpha$ limit. The dotted line is the cumulative redshift distribution for all the counterparts from Barger et al. (1999a) with two of the source identifications corrected as in Smail et al. (1999a) and the blank-field/ERO candidates placed at $z = 4$.

First results from spectroscopic surveys of the submm population are beginning to appear. In particular a Keck II spectroscopic survey of possible counterparts to the submm sources in our survey has recently been published (Barger et al. 1999a). Identifications were attempted for all the galaxies bright enough for reliable spectroscopy within the SCUBA error-boxes. This resulted in spectroscopic redshifts or limits for 24 possible counterparts to 14 SCUBA sources. The median $I$-band magnitude of the counterparts is $I = 22.4$, the equivalent depth for identifying candidates in a blank field submm survey would be closer to $I \sim 23$, stretching the capabilities of even the largest telescopes. In a number of cases the spectral properties of the candidate counterparts suggested that they were likely to be the source of the submm emission (Barger et al. 1999a), in others the identification of a radio counterpart (e.g. Ivison et al. 1999), or the unusual optical-NIR colors or a candidate (see §4) or morphologies add support to the identification of the submm emission as arising from a particular galaxy. For two sources we have been able to confirm the proposed galaxy as the submm source through the detection of redshifted CO emission in the millimeter at the redshift of the optical counterpart (Frayer et al. 1998; 1999). The reliable spectroscopic identifications include a $z = 2.8$ dusty type-2 AGN/starburst (Ivison et al. 1998); a $z = 2.6$ starburst (Barger et al. 1999a; Ivison et al. 1999); a $z = 3.2$ type-1 AGN (Ivison et al. 1999), the first example of the sub-mJy submm population identified; and the lowest redshift confirmed
source, a $z = 1.06$ ring galaxy (Soucail et al. 1999). The spectroscopic observations are thus consistent with the photometrically-derived redshift limits for the bulk of the population, and also provide information about the dominant emission processes in individual galaxies. In particular, the spectra give a useful indication of the relative fractions of AGN and starbursts in the submm population (Ivison et al. 1999).

But for over half the submm sources the results are more ambiguous with none of the galaxies with spectroscopic identifications within the submm error-box showing unusual spectral features, colors or morphologies. This leaves open the possibilities that either the submm emitting region is so highly obscured that it is invisible in the restframe optical/UV, a not unreasonable suggestion, or that the submm source has a fainter optical counterpart and remains unidentified in the spectroscopic survey. To distinguish between these alternatives and attempt to determine the redshift distribution of a representative sample of the faint submm population we have to resort to other spectroscopic indicators, which while admittedly cruder have the advantage of not relying on the identification of an optical counterpart for the submm source. In particular this is the only way to tackle those sources with no visible counterparts in the optical (e.g. Hughes et al. 1998; Smail et al. 1998) as well as providing useful information on the small proportion of sources with very red counterparts seen only in the near-infrared (Smail et al. 1999a). General constraints on the likely redshift distribution of faint submm sources come from the spectral shape of dust emission in the restframe far-infrared (Hughes et al. 1998) and the combination of this with radio information (Carilli & Yun 1999; Blain 1999).

As discussed by Hughes et al. (1998), the ratio of 450- and 850-µm fluxes can be used as a crude redshift indicator. Their analysis of the information provided by the 450-µm non-detections of the five 850-µm sources in the HDF suggested that the galaxies all lay at $z > 1$. A similar constraint arises from assuming that the same population of sources are being detected at 450 and 850 µm (an assumption which is supported by Eales et al. 1999) and determining the flux ratio between the two wavelengths at a fixed source surface density. The 450-µm counts are 1000 deg$^{-2}$ at a flux limit of 20 mJy, the equivalent surface density is achieved at 850-µm at ~ 6.5 mJy. Thus we obtain a typical $S_{450}/S_{850}$ ratio of $S_{450}/S_{850} \sim 3$ suggesting that the median redshift for the population is $z < 2$.

Another other method has been recently developed to estimate redshifts for faint submm sources using the 850 µm to 1.4 GHz spectral index, $\alpha^{850}_{1.4}$ (Carilli & Yun 1999). This technique relies upon the good correlation between the strength of the far-infrared emission (reprocessed UV/optical radiation from massive stars) and radio (synchtron emission from electrons accelerated in the supernovae from massive stars) in local star-forming galaxies (Condon 1992). The decline in emission from dust at longer wavelengths is eventually overtaken by the rising synchtron emission to produce an upturn between the submm and radio regimes around 3 mm. This feature is seen in the SEDs of both AGN and starburst galaxies (see examples in Ivison et al. 1998, 1999) and as proposed by Carilli & Yun (1999) the spectral index in this region can provide a crude redshift estimate. The spectral index has the behaviour that it is larger for higher redshift sources and Carilli & Yun were able to show that the redshift predictions from $\alpha^{850}_{1.4}$ based on local templates spectra and model SEDs were
in good agreement with the observed redshifts for a small sample of distant submm sources. The index also has the useful property that contamination by radio emission from an obscured AGN will tend to reduce the value of $\alpha_{850}^{1.4}$ giving a low redshift estimate. Thus $\alpha_{850}^{1.4}$ can be used to place robust lower limits on the redshifts of the submm population.

We have used deep VLA 1.4-GHz maps of the seven clusters in our survey to measure or place limits on the radio flux from the submm sources. To make these limits as conservative as possible we have used the radio flux for the brightest radio counterpart within each submm error-box, irrespective of whether there are other candidates which are preferred for other reasons. This means that we obtain a strong lower limit on $\alpha_{850}^{1.4}$, and hence on the source redshift, independent of the exact source identification. The radio maps have a typical $1\sigma$ sensitivity of $\lesssim 10\mu$Jy in the source plane and we identify radio counterparts to around half of the submm sources, with useful limits on the remainder. Using the various spectral models from Carilli & Yun (1999) we can transform these $\alpha_{850}^{1.4}$ measurements and limits into redshift ranges, $z_{\alpha}$, for each source.

We plot in Fig. 2 the cumulative redshift distribution derived from the radio/submm spectral analysis of the sources in our survey (Smail et al. 1999b). We show two curves, the first makes the most conservative assumption that each source without a reliable spectroscopic identification in Barger et al. (1999a) lies at the minimum redshift allowed by the observed spectral index or 3$\sigma$ lower limit (typically assuming an SED similar to Arp 220). The other curve assumes that the sources have uniform probability of lying anywhere in the redshift range allowed by their $\alpha_{850}^{1.4}$ index (with a maximum redshift for the population of $z = 8$). These distributions are compared to that obtained by Barger et al. (1999a) in their spectroscopic follow-up of these sources (where the two blank field sources and the recently identified ERO counterparts of Smail et al. (1999a) are all placed at $z = 4$). The median redshift for the complete spectroscopic sample, including both the reliable and possible counterparts, is $< z > \sim 2.5$ equivalent to the lower limit determined from our most conservative spectral index analysis. Distributing the sources in a more reasonable manner within their allowed range for $z_{\alpha}$ leads to median redshifts closer to $< z > \sim 3–4$.

Our conclusions about the source redshifts based upon both the $S_{450}/S_{850}$ ratio and $\alpha_{850}^{1.4}$ spectral index are sensitive to the assumed dust temperature, $T_d$, in the sources. For both estimators reducing $T_d$ will allow lower median redshifts for the population (see Blain 1999). However, only if we force the entire submm population to have a characteristic dust temperature less than 30 K can we start to push the median redshift much below $< z > = 2$.

We conclude that a variety of constraints from the observed spectral properties of the submm population, as well as detailed spectroscopic observations of a small number of robustly identified sources (Ivison et al. 1998, 1999; Barger et al. 1999a), suggest that the median redshift of the submm population lies in the range $< z > \sim 2–3$, with few if any luminous submm galaxies at $z \lesssim 1$. The submm fluxes of all the sources detected in published surveys lie in the range $S_{850} \sim 0.5–10$ mJy, assuming they lie at $z \gtrsim 1$ then their luminosities are $\log_{10} L_{\text{FIR}} \sim 12–13$ and so they all class as ultraluminous infrared galaxies.
Figure 3. ERO counterparts to two submm sources in our survey (Smail et al. 1999a). The two panels on the left show a deep, 0.6′′-resolution Keck II I-band image and a UKIRT K-band image of the field of SMM J09429+4658, overlayed on these are the 850-µm SCUBA map and a deep 1.4-GHz VLA map respectively. The two panels on the right show the equivalent data for the field of SMM J04433+0210. The faintest sources visible in the I-band exposure have $I \sim 25.5$–26.0, while the K-band images reach to $K \sim 20.5$. The original candidate counterparts for the submm sources are marked on the K images, as well as the new ERO candidates, H5 for SMM J09429+4658 and N4 for SMM J04433+0210. Each panel is 30′′ square and is centred on the nominal position of the 850-µm peak (absolute accuracy of $<3′′$). The relative radio-optical astrometry is better than 0.4′′ and hence the radio source close to the bright galaxy at the top of the SMM J09429+4658 frame is not coincident with it.

4. The Nature of the Faint Submm Population

We are still at an early stage in the study of the faint submm population and so the following discussion will concentrate on the results from the SCUBA lens survey for which a wide range of follow-up has been published. To briefly summarise the status of this survey. There are 15 non-cluster submm sources in the survey, of these around five have spectroscopic identifications which we believe reliably identifying these galaxies as the submm sources (two of these have been subsequently confirmed via detections in CO). A further three sources have either counterparts with unambiguous radio identifications or extreme optical-near-IR colors which allow us to identify them, and two more are in optically blank fields. This leaves five sources which have ambiguous identifications.

Starting with those galaxies with spectroscopic identifications, these all have relatively bright optical counterparts and a high proportion show multiple components in optical/near-IR – on separations of $\leq 2$–3″ (e.g. Ivison et al. 1998, 1999), at the galaxy redshifts this scale is equivalent to $\sim 10$ kpc. This lends weight to the suggestion that mergers and interactions are a crucial trigger of activity in distant ULIRGs (Smail et al. 1998; Lilly et al. 1999) as they are for more local examples. The identification of submm sources with merging systems suggests that we should properly view them as ‘events’ rather than galaxies.

To search for any extremely red counterparts, $(I - K) > 6$, which could have been missed in the optical identifications we have used UKIRT to obtain near-IR imaging of our fields down to $K \gtrsim 20$. We have so far identified two possible ERO counterparts to submm sources in our survey (Fig. 3, Smail et al. 1999a), both previously identified with bright $z \sim 0.5$ spiral galaxies, with the bulk of the submm error-boxes containing galaxies with optical–near-IR colors more typical of the general field, $(I - K) \sim 2$–4. Deeper K-band imaging of one submm source with a reliable radio position has also provided an identification...
of a $K \sim 22$ counterpart, the optical limit on this galaxy is $I \gtrsim 24$. The two submm error-boxes which were ‘blank’ ($I \gtrsim 25$) in the optical search undertaken by Smail et al. (1998) show no near-infrared candidates to $K \sim 21$.

The ERO counterparts account for 15% of the submm population. If the optically ‘blank’ fields also contain EROs the proportion of submm sources with highly reddened counterparts will rise to 30%. The implied surface densities of submm-bright EROs are consistent with the number of EROs detected in targeted SCUBA observations (e.g. Dey et al. 1999) and suggest that around half of the ERO population are dusty, star forming galaxies at moderate/high redshifts (Smail et al. 1999a).

Although currently incomplete, we are slowly building up a picture of the population of distant, luminous submm galaxies which dominate the SMBR at wavelengths around 1 mm. The fact that the submm population detected by SCUBA can account for all of the COBE background indicates that a large fraction of the stars in local galaxies could be formed in these systems. The characteristics of the submm galaxies are similar to those of local ULIRGs, except that they contribute a submm luminosity density at early epochs that is at least an order of magnitude greater than the corresponding local population. One goal is to use this population 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 at high redshift (Smail, Ivison & Blain 1997; Hughes et al. 1998; Blain et al. 1999b). In this way a complete history of star formation in the Universe can be constructed.

From the analysis discussed in §3 we can state that the luminous submm population is roughly coeval with the more modestly star-forming galaxies selected by UV/optical surveys of the distant Universe (e.g. Steidel et al. 1999). 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 dustier and probably therefore more chemically enriched. Converting the submm luminosities into an equivalent star formation density is a very uncertain process (e.g. Blain et al. 1999b), nevertheless, most reasonable conversions result in a star formation density in the submm population which is a factor of several higher than that seen in UV/optically selected samples at high redshift (Fig. 4), even after applying similarly uncertain corrections to the latter for the effects of dust obscuration on the UV luminosities. Although this comparison remains uncertain, it does show that the submm population needs to be explained by any models that claim to describe the star formation history of the Universe.

As with local ULIRGs, there is uncertainty over the exact contributions from AGN and starbursts to the far-infrared luminosity density of the SCUBA population. This adds another possible source of contamination to the comparison shown in Fig. 4. The identification and removal of obscured AGN from the submm sample can be achieved through searches for hard X-ray emission with Chandra. For all but the most heavily enshrouded systems ($\log N(\text{H}I) \gtrsim 24$) the hard X-ray emission should still be detectable from the central AGN (Gunn 1999). These searches will also provide an estimate of the total contribution from the dust-obscurced AGN to the X-ray background (Almaini et al. 1998; Gunn 1999). Calculations which use the X-ray background to constrain the number of obscured AGN indicate that at most 20–30% of the SCUBA sources...
Figure 4. The estimated star formation densities at different epochs from UV/optically-selected samples (nominally corrected for extinction) compared to that estimated from the SCUBA population assuming the conservative redshift distribution from Fig. 2 (Blain et al. 1999b). The lower-bound on the SCUBA point shows the maximum correction for AGN contamination in the sample as discussed in the text. The symbols follow those in Blain et al. (1999b) with the exception that the filled circles show the latest results by Steidel et al. (1999) and the cross that from Yan et al. (1999).

...could harbor an obscured AGN. The incomplete observations available for the submm population suggest that $\gtrsim 20\%$ of the submm population show obvious spectral signatures of an AGN. We stress, however, that this does not mean that the AGN dominates the emission in the submm and so the correction indicated in Fig. 4 remains uncertain.

One interesting issue which remains is what are the descendents of the submm population? They have high bolometric luminosities, large dust masses ($10^8 M_\odot$, Ivison et al. 1998, 1999) and large gas reservoirs ($10^{11} M_\odot$, Frayer et al. 1998, 1999). These properties are consistent with on-going massive star formation in these systems at rates $\gtrsim 1000 M_\odot yr^{-1}$, which given the available molecular gas supply could continue for $10^8$ yrs and result in the formation of an entire $L^*$ galaxy at $z \gtrsim 2$. The submm population also show morphological similarities to local merging ULIRGs which are thought to evolve into elliptical galaxies. The circumstantial evidence thus points towards the submm sources being precursors of elliptical galaxies. Assuming that the luminous submm phase lasts for a few dynamical times of the remanent halo, $\sim 1$ Gyr, the volume density of these galaxies at high redshifts is $\sim 2-4 \times 10^{-4} Mpc^{-3}$, high enough to allow all massive ellipticals to be formed in this manner. Arguments have been advanced for a number of years for the prompt and synchronised formation of a large fraction of the luminous elliptical galaxy populations in the richest clusters at $z \gtrsim 3$ (Bower, Lucey & Ellis 1992; Ellis et al. 1997) due to their extreme homogeneity both within individual clusters and between clusters. If the SCUBA sources are identified with the earliest, obscured phases of this activity then we would expect the submm sources to be clustered on scales comparable to that of the putative proto-clusters at these early epochs, $\sim 10$ Mpc or 20 arcminutes (Governato et al. 1998). Thus strong clustering of SCUBA sources
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is a clear prediction of the identification of these galaxies with proto-ellipticals, searching for such structures should be a high priority for future submm surveys.

An equally interesting issue is the relationship between the submm population and the Lyman-break galaxies (Steidel et al. 1999). These objects appear to have typically lower SFRs and less dust than the submm galaxies, although they have a substantially higher number density. We would therefore identify the submm galaxies with the most energetic mergers which form massive, young ellipticals and more quiescent star formation due to secular evolution in disk systems with the Lyman-break objects. Detailed observations of the submm population should thus provide much needed observational input to models of the formation and evolution of massive galaxies (Blain et al. 1999b). In particular we anticipate CO detections of more submm galaxies to study the kinematics of these systems and hence determine their masses.

5. The Future

On-going and planned upgrades to SCUBA and the JCMT will improve the sensitivity and effectiveness of this world-class facility. Looking slightly further ahead there is a proposal for a wide-field submm imager, SCUBA–2, based upon new detector technology and capable of providing statistically reliable samples of submm galaxies. Such samples will enable us to break new ground in crucial areas such as clustering of submm sources, necessary to understand the evolutionary status of this population relative to other classes of high redshift source. However, at 850 $\mu$m the large JCMT beam will remain the main restriction to probing deeper into the submm counts to identify the turn-over which should occur around $\sim 0.5–1$ mJy. This turn-over has important implications for models of the formation and evolution of obscured galaxies and the approach we have taken of employing massive gravitational lenses to increase the sensitivity and resolution of the SCUBA maps is well suited to tackling this problem. An equivalent length exposure to that obtained with SCUBA on the HDF (Hughes et al. 1998) but instead targeted on a well-constrained cluster lens such as Abell 370 would constrain the form of the 850-$\mu$m counts down to 0.3 mJy ($3\sigma$), probing the region where the counts should turn over if they are to remain consistent with the COBE measurements of the SMBR.

In the long term the proposed Atacama Large Millimeter Array (ALMA) will mark an enormous leap forward in the capabilities of ground-based submm mapping and imaging. The current optical/near-infrared identification programs for the minute samples of relatively bright submm sources provided by SCUBA are stretching the capabilities of 4- and 10-m telescopes. The numbers and characteristics of the sources likely to be uncovered with ALMA will probably exceed the follow-up capabilities of the available facilities (including NGST), even if we restrict ourselves to merely near-infrared imaging and limited spectroscopy. It may be that we have to abandon entirely short-wavelength observations of this population and rely on what we can observe in the submm and radio. The other option is to tailor the submm surveys for easier follow-up. In this regard we are pursuing submm imaging of fields around bright, $V \sim 12$, high-latitude stars (which are invisible in the submm). These can then be used as natural guidestars for high-order adaptive optics systems on 4- and 8-m telescopes, facilitating deep high-resolution imaging and spectroscopy of possible counterparts.
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