An investigation of the submillimeter background radiation using SCUBA and Spitzer


ABSTRACT
We investigate the redshift dependence of the contribution to the extragalactic far-infrared/sub-millimeter background from galaxies detected by the Spitzer Space Telescope at 8μm and 24μm. Using seven-band optical to mid-infrared photometry, we estimate photometric redshifts for the Spitzer sources which appear to be mostly L* galaxies at a median redshift of z = 1.0. These sources, extracted from deep 8μm and 24μm mosaics of the CUDSS 14-hour field with 5σ limits of 5.8μJy and 70μJy respectively, exhibit significant 850μm and 450μm emission as observed by SCUBA. At 850μm, after removing ≥ 4σ sources and those securely identified in our previous cross-matching paper, we measure stacked flux at the significance level of 4.4σ from the full 8μm and 24μm galaxy catalogue respectively. At 450μm, flux is detected from all 8μm galaxies at the level of 3.5σ, while there is no significant emission from the 24μm galaxies. We find that the 850μm flux is emitted almost exclusively at z ≳ 1.3 from the Spitzer sources with 0.44mJy (4.7σ) per 8μm source and 0.51mJy (2.8σ) per 24μm source. This corresponds to a contribution of (16 ± 3)% toward the 850μm extra-galactic background from the 8μm sources and (5.0 ± 1.8)% from the 24μm sources. At 450μm, only the 8μm sources within the redshift interval 1 < z < 2 exhibit significant emission with an average flux per source of 3.35mJy (3σ). This is a contribution of (37 ± 12)% to the 450μm background.

Subject headings: infrared: galaxies

1. Introduction
Steady advances toward a thorough understanding of the population of high redshift sub-millimeter (submm) sources uncovered by the Sub-millimeter Common User Bolometric Array (SCUBA) and the Max-Planck Millimeter Bolometer (MAMBO) have been made since their detection in the first deep submm survey by Smail, Ivison & Blain (1997). The two most controversial issues concerning their nature have been, firstly, identification of their dust-cloaked energy source and secondly, how they relate to local systems.

The question regarding the energy source has now been largely satisfied. The lack of strong X-ray emission from these sources (eg. Ivison et al. 2000b; Fabian et al. 2000; Alexander et al. 2003; Almaini et al. 2003; Waskett et al. 2003; Alexander et al. 2005) suggests that their submm flux is dominated by re-radiated emission from intense star formation, rather than AGN output. Observations constrain the net contribution of AGN activity to the level of ~ 30% (see Chapman et al.
the background is of the greatest importance be-

nature of the individual sources that constitute
background radiation as a whole. Determining the
representative of the extragalactic far-infrared/submm
in the bright SCUBA samples may not be repre-

sentative in the submillimeter waveband (Fixsen et al.
1998). Yet the bright SCUBA sources for which
there are redshifts may represent only a tiny frac-
tion of this background. The problem is that the
far-IR/submillimeter background is much brighter
(\sim 30 times greater in terms of $\nu I_\nu$) where it peaks
at \sim 200\mu m than it is at 850\mu m, the wavelength
of the SCUBA surveys. At 850\mu m, around 30% of
the background can be resolved into sources brighter than 3mJy (eg. Hughes et al. 1998;
Eales et al. 2000; Smail et al. 2002; Webb et
al. 2003b; Chapman et al. 2005). Estimates of
this fraction extend up to 60% for sources down
to 1mJy (eg. Smail et al. 2002; Chapman et
al. 2005). The sources for which Chapman et
al. (2005) measured redshifts are radio-detected
sources with 850\mu m fluxes brighter than \sim 3 mJy.
Using estimates of the spectral energy distribu-
tions of individual galaxies Chapman et al. (2005)
concluded that their sample represents 30% of the
background at 850\mu m but only about 2% of the
background at 200\mu m.

Therefore, despite the success of the work on
the brighter SCUBA samples, there are many
unanswered questions. For example, is the redshift
distribution that Chapman et al. (2005) measure
representative of the far-IR/submm background as
a whole? Until the background at 200\mu m can be
directly resolved into individual sources, the next
best alternative is to study the SCUBA sources at
fainter 850\mu m fluxes. Unfortunately, here one hits
the obstacle of confusion.

There are two ways round this obstacle. One is
to exploit gravitational lensing to mitigate the
problem (eg. Smail et al. 2002). The second
is the approach we adopt in this paper, using
the SCUBA images to estimate the submillimeter
fluxes of objects selected in other wavebands for
which there are already accurate positions. Pea-
cock et al. (2000) used this reverse procedure by
stacking 850\mu m SCUBA detected emission from
optical sources in the Hubble Deep Field North.
This study identified significant submm emission
from galaxies with high UV star formation rates.
Serjeant et al. (2003) repeated this work replacing
the optical data with 15\mu m ISO sources, but
measured no emission. However, the much im-
proved sensitivity and resolution of the Spitzer

2005, and references contained therein). However,
the question regarding their relationship with the
local galaxy population remains only partially an-
dressed.

Finding the connection between distant submm
sources and local galaxies requires an understand-
ing of their evolution. Sources detected in sur-
veys with SCUBA and MAMBO have extremely
high estimated star formation rates (100 - 1000
$M_\odot$ yr$^{-1}$), enough to rapidly form a massive ellip-
tical (Smail, Ivison & Blain 1997; Hughes et al.
1998; Lilly et al. 1999; Dunne, Eales & Edmunds
2003). However, it is not clear from studies of
the spatial density or clustering of submm sources
whether a direct link between local ellipticals and
the submm population can be made quite so con-
fidently (Fox et al. 2002; Scott et al. 2002).

The main observational limitation in under-
standing the SCUBA population is the relatively
large beam size. This gives rise to a correspond-
ingly large uncertainty on extracted source posi-
tions and also means that confusion is a concern
in deeper observations. One of the key ingredients
needed to help resolve the evolutionary relation-
ship between local and distant submm galaxies,
determination of submm galaxy redshifts, is there-
fore especially difficult. A successful technique
is to observe the sources using radio interferom-
etry, as the surface density of radio sources is suf-

ficiently low to make confident associations with
coincident submm sources. The high astromet-
ric precision in these radio data greatly eases the
identification of optical counterparts for follow-up
spectroscopy. Around two thirds of the submm
sources detected at 850\mu m appear to have radio
counterparts (eg. Ivison et al. 2002; Borys et al.
2004), but because the ratio of radio to submm
flux decreases with increasing redshift (Carilli &
Yun 1999), radio observations are biased toward
lower redshift objects ($z \sim 3$). This method was
recently applied by Chapman et al. (2005) using
Keck spectroscopy to determine the redshifts of
73 submm sources cross-identified in VLA maps.
They found a median redshift of $z \sim 2.2$.

A frequently ignored issue is that the sources
in the bright SCUBA samples may not be repre-
sentative of the extragalactic far-infrared/submm
background radiation as a whole. Determining the
nature of the individual sources that constitute
the background is of the greatest importance be-
cause approximately 50% of the entire extragalac-
tic background radiation (minus the CMB) is radi-
ated in the submillimeter waveband (Fixsen et al.
1998). Yet the bright SCUBA sources for which
there are redshifts may represent only a tiny frac-
tion of this background. The problem is that the
far-IR/submillimeter background is much brighter
(\sim 30 times greater in terms of $\nu I_\nu$) where it peaks
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the optical data with 15\mu m ISO sources, but
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proved sensitivity and resolution of the Spitzer
Space Telescope (Werner et al. 2004) recently enabled Serjeant et al. (2004) to statistically detect 5.8\(\mu m\) and 8\(\mu m\) sources in 850\(\mu m\) and 450\(\mu m\) SCUBA data. Finally, Knudsen et al. (2005) recently detected significant 850\(\mu m\) emission from distant red galaxies selected by J−K>2.3, finding that these sources are probably strong contributors to the far-IR/submm background.

In this paper, we stack 450\(\mu m\) and 850\(\mu m\) flux observed by SCUBA at the position of 8\(\mu m\) and 24\(\mu m\) Spitzer sources in the Canada-United Kingdom Deep Sub-millimeter Survey (CUDSS) 14-hour field. From these data, we estimate the fractional contribution from Spitzer sources to the extragalactic background at 850\(\mu m\) and 450\(\mu m\). Using a combination of ground-based optical, near infrared and Spitzer 3.6\(\mu m\) and 4.5\(\mu m\) observations, we compute photometric redshifts for the Spitzer sources, to investigate the epoch at which their attributed submm flux is emitted. This paper follows on from our previous paper (Ashby et al. 2005) where the forward approach of cross-identifying Spitzer sources with submm sources was carried out.

The layout of this paper is as follows: In Section 2 we describe the data. Section 3 details our photometric redshift estimation. Stacking is carried out in Section 4. We conclude with a summary and discussion in Section 5.

2. Data

Observations of the CUDSS 14 hour field analysed in this paper comprise three distinct sets: 1) Mid-infrared observations using the Spitzer Space Telescope, 2) Submm data observed with SCUBA, 3) Ground-based optical and near infrared observations.

2.1. Spitzer Space Telescope Data

The Spitzer observations discussed in this paper were obtained as part of the Guaranteed Time Observing program number 8 to image the extended Groth strip, a 2° × 10′ area at \(\alpha \sim 14^h 19^m, \delta \sim 52^\circ 48′\) (J2000) with the Infra-red Array Camera (IRAC; Fazio et al. 2004) and Multi-band Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004). Approximately 90% of the CUDSS 14 hour field falls robustly inside this area, the remaining 10% in the south-east corner having poor or no coverage. This corner was cropped in all data sets presented here (see Figure 1).

Carrying on from our identification paper (Ashby et al. 2005), we have used the 8\(\mu m\) IRAC and 24\(\mu m\) MIPS source positions for the stacking. The fraction of sources detected in the higher frequency IRAC data that are dusty submm emitters is expected to be lower than in the 8\(\mu m\) and 24\(\mu m\) data. In addition, the sensitivity of these shorter wavelength data is much higher than the SCUBA maps so that the stacking tends to sample noise rather than the detectable population of faint sources. Indeed, Serjeant et al. (2004) failed to detect significant submm emission from Spitzer sources observed in the IRAC 3.6\(\mu m\) and 4.5\(\mu m\) channels in SCUBA observations of the Hubble Deep Field. The converse is true of the longer wavelength MIPS data where the number density of sources seen is too low to act as a good probe of the submm emission observed in our SCUBA maps. The 5\(\sigma\) point source sensitivity of the 8\(\mu m\) and 24\(\mu m\) data is 5.8\(\mu Jy\) and 70\(\mu Jy\) respectively.

Although we made no use of the 3.6\(\mu m\) and 4.5\(\mu m\) IRAC detected sources in the stacking directly, photometry from these channels was combined with the ground-based optical data for computation of photometric redshifts in Section 3. The 5\(\sigma\) point source sensitivity of both the 3.6\(\mu m\) and 4.5\(\mu m\) data is 0.9\(\mu Jy\).

There are 553 8\(\mu m\) sources that fall within the 850\(\mu m\) map area and 511 that fall within the 450\(\mu m\) map. Of the 24\(\mu m\) sources, 141 fall within the 850\(\mu m\) map and 133 within the 450\(\mu m\) map. All of the 24\(\mu m\) sources are detected at 8\(\mu m\).

2.2. Sub-mm data

The SCUBA observations amount to 63 hours worth of data taken on 20 different nights over the period from March 1998 to May 1999 at the James Clark Maxwell Telescope (JCMT). The final 450\(\mu m\) and 850\(\mu m\) maps of the \(\sim 7′\times 6′\) survey region were created by combining many 'survey units’. Each survey unit was observed for approximately one hour with a 64-point jiggle pattern (ensuring they are fully sampled), nodding JCMT’s secondary mirror and chopping by 30″ in right ascension.

The data reduction was carried out with the SURF package (Jenness 1997) and a noise map
created using a Monte Carlo technique to simulate the noise properties of each of SCUBA’s bolometers. We refer the reader to Eales et al. (2000) for more specific details of the data reduction.

We work with beam-convolved signal-to-noise (S/N) maps in this paper, to maximise source detection. Since the goal is to detect faint SCUBA sources buried in the map noise, prior to convolving with the beam, we subtracted SCUBA sources based on their sub-mm S/N and their identifications in our previous paper (Ashby et al. 2005). For the 850μm data, we made three maps with different combinations of SCUBA sources removed to assess whether the stacking is influenced by this removal process. These three combinations are: 1) Removal of only the sources listed in Ashby et al. (2005) with a secure Spitzer identification. A ‘secure’ source is defined as having a bright 8μm positionally coincident (r < 10′′) Spitzer counterpart with IRAC-MIPS colors indicative of a high-redshift dusty source (see Huang et al. 2004). Ashby et al. (2005) made 7 secure identifications. 2) Removal of the secure sources along with the remaining 5 sources detected by SCUBA with significance ≥ 4σ. 3) Removal of the 12 sources in case 2 along with the remaining 6 sources having a ‘possible’ Spitzer identification at 8μm. A source identification is classified as ‘possible’ when selected from multiple co-incident sources. As in case 1, the most likely counterpart is chosen based on IRAC-MIPS colors. Removing this last combination of 18 sources leaves only 2 of the 23 SCUBA sources in the 850μm data (three fall in the cropped south-eastern corner), both with significances of 3.0σ (Webb et al. 2003a).

Sources were removed from the raw SCUBA maps by subtracting the beam profile at the position of the source, scaled by the source flux. There are no directly detectable significant sources in the 450μm data, hence no sources were removed from the 450μm map. Figure 1 shows the beam-convolved S/N map at 850μm with the secure + ≥ 4σ sources removed and the (unmodified) map at 450μm. The 8μm and 24μm Spitzer source positions within the CUDSS 14h area having z > 1.3 are over-plotted on the 850μm map and those with 1 < z < 2 are over-plotted on the 450μm map, to coincide with the findings of Section 4.2.

2.3. Optical & Near Infrared Data

In addition to the IRAC matched photometry, we also matched to optical and near-infrared ground-based data. For the optical photometry, we extracted U, B, V & I fluxes from the Canada-France Deep Fields survey (CFDF) (McCracken et al. 2001) imaged with the 4.0m Blanco Telescope and the Canada-France-Hawaii Telescope (CFHT). Like the IRAC photometry, fluxes were summed in 3′′ diameter apertures. The 3σ point source sensitivities in AB mags are 27.71, 26.23, 25.98 and 25.16 for U, B, V & I respectively.

For the near-infrared photometry, we matched to our own SExtracted (Bertin & Arnouts 1996) catalogue of the K-band image of Webb et al. (2003a), observed with the CFHT using the CFHTIR camera. The K-band data reach a depth of K_{AB} ∼ 23.

3. Photometric Redshifts

From the matched aperture photometry in U, B, V, I & K as well as the IRAC 3.6μm and 4.5μm channels, we obtained photometric redshifts for the 8μm and 24μm sources using the HyperZ redshift code (Bolzonella et al. 2000). We decided not to use photometry from the two longest-wavelength IRAC channels, 5.8μm & 8μm, because these data are less sensitive than the two shortest-wavelength channels, they are more affected by dust emission features (Lu et al. 2003) and the spectral templates are uncertain at these wavelengths (specifically, the contribution from PAHs). We excluded sources with poor quality measurements at 3.6μm and 4.5μm, although we did not exclude sources with poor measurements or non-detections in the longer wavelength bands.

The local galaxy spectral energy distributions (SEDs) packaged with HyperZ are those given by Coleman et al. (1980), with an extrapolation into the infrared using the results of spectral synthesis models. The lack of any empirical basis for these templates at wavelengths > 1μm is clearly unsatisfactory since our photometry includes both near-infrared and mid-infrared measurements. Therefore, we constructed our own set of templates in the following way. Mannucci et al. (2001) list empirical SEDs extended from 0.1μm to 2.4μm for the Hubble types E, S0, Sa, Sb and Sc. We extended these out to 6μm using the average SEDs
for disk galaxies and elliptical galaxies listed in Table 3 of Lu et al. (2003) using the disk-galaxy SED for all Hubble types apart from ellipticals. The one disadvantage of these templates is the lack of a template for an irregular galaxy, and we therefore retained the HyperZ template for an Im galaxy, extending this into the mid-infrared using the average disk-galaxy SED from Lu et al. (2003).

We tested the accuracy of our photometric redshifts by estimating redshifts for the 8\(\mu\)m sources in the field that have spectroscopically confirmed redshifts. There are 61 galaxies from the Canada-France Redshift Survey (CFRS) (Lilly et al. 1995) that are detected by Spitzer at 8\(\mu\)m and an additional four objects that are possible SCUBA detections with spectroscopic redshifts (Chapman et al. 2005). Figure 2 shows the photometric redshift estimates plotted against the spectroscopic redshifts. The agreement is fairly good with the scatter, defined as \(\sqrt{\sum (\Delta z/(1+z))^2/N}\), equal to 0.217 for the CFRS sources and 0.161 for the four SCUBA galaxies. We note, however, that there are very few galaxies with spectroscopic redshifts at \(z > 1\). We are therefore less confident about the accuracy of estimates beyond this redshift, although the large bin size used when stacking by redshift in Section 4.2 will greatly reduce the impact of large errors.

Figure 3 shows the I-band magnitude versus photometric redshift for all the objects in our 8\(\mu\)m and 24\(\mu\)m catalogue. The curve shows the prediction for a non-evolving L\(_*\) galaxy, with the K-correction calculated using the SED for an Sbc galaxy. We have used the value for L\(_*\) given by Blanton et al. (2001). The diagram shows that the galaxies detected by Spitzer at 8\(\mu\)m are mostly L\(_*\) galaxies with a fairly small dispersion about this luminosity. This small dispersion is additional confirmation that our photometric-redshift technique works reasonably well (approximately 50% more scatter is seen if the Spitzer photometry is omitted in the redshift analysis).

4. Stacking analysis

The stacking process determines the sum of the submm flux detected at the position of Spitzer
sources and its significance. In this work, we calculate the total weighted flux, given by

$$f = N(\sum_i f_i \sigma_i^{-2}) / (\sum_i \sigma_i^{-2}), \tag{1}$$

where \(f_i\) is the submm flux taken from the beam-convolved map at the position of the \(i\)th Spitzer source, \(\sigma_i\) is its error and \(N\) is the total number of sources stacked.

We measure the significance of the stacking in two separate ways:

- The first uses the Kolmogorov-Smirnov (KS) test to quantify the significance of the discrepancy between the distribution of S/N drawn from the submm map at the position of the Spitzer sources and the S/N distribution of all pixels in the entire map. If the former distribution is positively skewed with respect to the latter, then this is attributed to the detection of faint SCUBA sources.

- The second is based on the significance of the actual total weighted flux measured. The formal error on \(f\) is defined as

$$\sigma_f = N / \sqrt{\sum_i \sigma_i^{-2}}. \tag{2}$$

One can then define the significance \(\beta = f / \sigma_f\). However, Serjeant et al. (2003) showed using Monte Carlo simulations that \(\beta\) is not normally distributed. We correct for this with our own Monte Carlo simulations (see below).

We determined the distribution of \(\beta\) and the KS significance by carrying out Monte Carlo simulations for each of the four SCUBA datasets considered in this paper (the three 850\(\mu\)m maps and the
450µm map). 100,000 realisations of the Spitzer source positions were performed per dataset. We found that the distribution of KS significance is perfectly Gaussian in every case, whereas the distribution of $\beta$ is skewed positively by an amount depending on the submm dataset.

To account for the non-Gaussianity in $\beta$, we used its distribution function calculated from the Monte Carlo analysis to make plots showing the relationship between $\beta$ and its equivalent Gaussian significance, $\beta_g$. All four SCUBA datasets gave linear relationships which were fitted as follows: 850µm secure $\beta_g = 0.79\beta - 0.15$; 850µm $\geq 4\sigma$ + secure $\beta_g = 0.95\beta - 0.09$; 850µm possible + secure $\beta_g = 1.01\beta - 0.22$; 450µm $\beta_g = 0.86\beta + 0.26$. From these relationships, it is apparent that the 850µm data with only secure sources removed would quite heavily over-predict the stacking significance if not corrected. The corrections for the remaining SCUBA data are fairly modest.

In this paper, all total weighted flux significances quoted are the corrected version $\beta_g$. Absolute errors quoted on the total weighted flux are those given by equation (2).

Despite the fact that the KS significance adheres to Gaussian statistics, we found that it often gives false peaks in simulations of alignment maps described in the following section, whereas the corrected weighted flux significance, $\beta_g$, does not. For this reason, we use $\beta_g$ to assess data alignment. However, in Section 4.2 where we discuss stacking Spitzer sources selected by redshift, we calculate both $\beta_g$ and the KS significance for comparison.

4.1. Stacking the full 8µm & 24µm catalogues

A crucial assumption in the stacking analysis is that the astrometric solutions of the Spitzer and SCUBA datasets are not offset from each other. We therefore tested the alignment of the SCUBA and Spitzer data by calculating $\beta_g$ for a range of offsets in RA and Dec added to the Spitzer source positions. The test plots this as a map with the x-axis corresponding to the RA offset and the y-axis the Dec offset. If the Spitzer data is well aligned with the SCUBA maps and if a significant detection is made, a peak in the vicinity of the origin should be apparent. This peak should be singular. If more than one significant peak is seen, then the alignment of both data sets cannot be established with confidence and the robustness of the detection must also be drawn into question.

Figure 4 shows the maps of $\beta_g$ over the 100″ range of offsets in RA and Dec spanned, for both 8µm and 24µm Spitzer sources stacked with the 450µm data and the 850µm data with secure + $\geq 4\sigma$ sources removed. The contours start at a significance of $2\sigma$ with intervals of 0.5$\sigma$. The more smoothly varying features of the 850µm plots relative to the 450µm plots reflects the larger beam size at 850µm.

Stacking the 8µm sources shows a clear detection at both 850µm and 450µm with peak significances of 4.4$\sigma$ and 3.5$\sigma$ respectively. The 850µm peak occurs at an offset of $(0'',-2'')$ and the 450µm peak at $(4'',0'')$. The results from stacking with the 24µm catalogue are less clear; at 850µm, there are two 2.9$\sigma$ peaks at offsets of $(5'',-10'')$ and $(-8'',12'')$ with a significance of 2.5$\sigma$ at $(0'',0'')$. There is no detection of the 24µm sources at 450µm.

To determine the significance of these offsets, we carried out Monte Carlo simulations of the stacking at 850µm and 450µm. For each realisation, we created a noisy synthetic SCUBA map and placed sources with fixed S/N by adding the SCUBA beam at random positions. After convolving the map with the beam, stacking was carried out, offsetting this randomized catalogue by varying amounts to produce a $\beta_g$ map, like those shown in Figure 4. We carried out 200 realisations for each of five different source S/N values.

Figure 5 shows the mean and scatter of the radial offset of the peak in $\beta_g$ from $(0'',0'')$ as a function of the significance of the peak. We found no discernible difference between the 850µm and 450µm results hence this plot serves for both wave-lengths. From the plot, we conclude that the peak of 4.4$\sigma$ seen in the significance map for the 8µm sources and 850µm data, occurs on average in the simulations at a radial offset of $r = 2.0'' \pm 1.5''$. The measured offset of $(0'',-2'')$ is therefore consistent with there actually being no misalignment between the 850µm SCUBA map and 8µm data. Similarly, at 450µm, the offset of $(4'',0)$ of the 3.5$\sigma$ peak is consistent with the expected offset of $r = 2.6'' \pm 1.7''$ for no misalignment. The implication that the 450µm and 850µm maps are well-
aligned is reassuring; as an additional check, we verified that this is the case from astrometry of point source calibrators acquired at both wavelengths throughout the CUDSS observing. The 24µm catalogue has the same astrometry as the 8µm catalogue since both are tied to the Two Micron All Sky Survey (2MASS; Cutri et al. 2003), hence we conclude that all datasets used in the stacking are properly aligned.

To summarise this section, we can make two statements. Firstly, there is significant emission at 850µm and 450µm from all 8µm Spitzer sources on average. From the 24µm sources, the total weighted flux has a significance of 2.5σ at 850µm but because the significance map is dual-peaked, this is a tentative detection. Secondly, the Spitzer data and the SCUBA data are well-aligned.

In the next section, we split the Spitzer catalogues by redshift to investigate the possibility of this detection being weakened by foreground/background Spitzer sources not truly associated with the observed submm emission.

4.2. Stacking by redshift

Having assigned photometric redshifts to the Spitzer catalogues, we can stack sources separated into redshift bins. The bin size must be large compared to the typical redshift uncertainty. In addition, the number of objects per bin must be
These detections were verified with the KS test. We applied the same Spitzer source redshift selections and chose the 850Å data with secure and possible sources removed. Figure 4 shows the results. In these plots, the S/N distribution of the full SCUBA map (the ‘map distribution’) is shown as an open histogram and the distribution of S/N at the redshift selected Spitzer source positions (the ‘source distribution’) as a shaded histogram. In all plots, bar that for the 450Å + 24Å data, excess emission from faint submm sources causes the source histogram to be clearly skewed positively with respect to the map histogram. The KS test quantifies the significances of these skews as follows: 850Å emission from the 8Å sources at 4.5σ, 850Å emission from the 24Å sources at 3.3σ and 450Å emission from the 8Å at 2.3σ. The 24Å sources are not detected at 450Å.

Table 1 summarises the results for all versions of the submm data. The weighted flux significances agree fairly well with the KS significances, although on the whole, they are slightly higher. The largest discrepancy occurs in the 850Å map with only secure sources removed. In this case, the 4σ submm sources and/or the submm identifications defined as possible by Ashby et al. (2005) are detected in the stacking.

5. Summary and Discussion

We have measured significant 850Å emission from Spitzer 8Å and 24Å sources and 450Å emission from the 8Å sources. The 5σ point source sensitivities of the Spitzer data are 5.8μJy at 8Å and 70μJy at 24Å. By computing photometric redshifts for the Spitzer sources using optical, near infra-red and Spitzer 3.6Å and 4.5Å photometry, we have been able to statistically identify the epoch from which this submm emission dominates. We find that the 850Å flux is almost exclusively emitted from Spitzer sources at redshifts z ≥ 1.3 up to the highest redshift of z ~ 4 we measure in our sample. Our most conservative estimate of this flux (i.e. having subtracted secure and possible SCUBA sources) is 0.44mJy per 8Å Spitzer source (4.7σ significance) and 0.51mJy per 24Å Spitzer source (2.8σ significance). At 450Å, the emission appears to peak around z ~ 1.5 with an average stacked flux per 8Å Spitzer source within 1 < z < 2 of 3.35mJy.

Fig. 5.— Results of Monte Carlo simulations to determine the variation of the mean and scatter of peak offset from (0′′, 0′′) in the significance maps as a function of the amplitude of the peak measured. Results plotted here apply to the 8Å sources and either 850Å or 450Å data.
Fig. 6.— Variation of total weighted flux of objects binned by redshift (median bin redshift plotted). Top left: The 850\,µm data stacked with the 8\,µm sources, where the solid, dashed and dot-dashed lines indicate secure, secure + \geq 4\sigma and secure + possible SCUBA source subtraction, respectively. Abscissae are plotted slightly staggered for clarity. Top right: The 450\,µm data stacked with the 8\,µm sources. Bottom left: 850\,µm data stacked with the 24\,µm sources. Bottom right: 450\,µm data stacked with the 24\,µm sources.

We can estimate the contribution our stacked flux makes to the extragalactic far-IR/submm background using the spectrum of Fixsen et al. (1998). According to their measurements, the background flux at 850\,µm is 0.14\,MJy/sr. The total weighted flux we measure from 8\,µm sources at \( z > 1.3 \) in our 850\,µm map with secure and possible sources removed is 0.022 \pm 0.004\,MJy/sr, a contribution of (16 \pm 3)\%. The 24\,µm sources at \( z > 1.3 \) are responsible for approximately one third of this with a fractional contribution of (5.0 \pm 1.8)\%. At 450\,µm, Fixsen et al. (1998) measure a background flux of 0.47\,MJy/sr. The weighted total flux from the 8\,µm sources with 1 < \( z < 2 \) in our 450\,µm data is 0.175 \pm 0.058\,MJy/sr, some (3.0\sigma significance).

Our estimate of the 850\,µm contribution to the background from 8\,µm sources is consistent with the fraction of (20 \pm 8)\% determined by Serjeant et al. (2004). Within their errors, Serjeant et al. (2004) find that the 450\,µm flux from 8\,µm sources is sufficient to account for all of the background radiation at this wavelength. This is in contrast to our findings that indicate a maximum contribution of approximately 50\%.

Including the flux of submm sources removed from the 850\,µm data gives a measure of the combined contribution of directly detected and stacked sources to the background at this wavelength. The secure and possible submm sources have a total weighted 850\,µm flux of (62 \pm 5)\,mJy. Adding this
to the stacked 850\,µm flux from the 8\,µm sources gives a total fractional background contribution of (29 ± 3)%. Webb et al. (2003c) estimate that Lyman break galaxies (LBGs) contribute ~ (20 ± 10)% of the 850\,µm background. Even making the extreme assumption that there is absolutely no overlap between the LBG and Spitzer 8\,µm population (but see Huang et al. 2005, who estimate an overlap of ~ 25%) the total fraction of the 850\,µm background that remains unaccounted for is at least 40%.

The average submm fluxes we measure in the stacking correspond to fairly regular systems. To demonstrate this, we can use the definition of an ultra-luminous infrared galaxy (ULIRG) set by Clements, Saunders & McMahon (1999). This stipulates that a ULIRG must have a luminosity of at least 10^{11.4}\,L_\odot measured at 60\,µm by the infra-red astronomical satellite (IRAS). With an assumed IRAS galaxy SED, the expected 850\,µm and 450\,µm flux can be calculated for a ULIRG at the median redshift of our catalogue, z = 1.0. Following Clements et al. (2004), we take the coolest and warmest IRAS galaxy SEDs from the sample of Dunne & Eales (2001) to estimate the range of submm emission expected. Using the SED of NGC958, which is dominated by cold dust at 20K, the expected submm flux from an object with a 60\,µm IRAS flux of 10^{11.4}\,L_\odot at z = 1.0 is 0.77\,mJy at 850\,µm and 2.06\,mJy at 450\,µm (h_{100} = 0.7, \Omega_m = 0.3, A = 0.7). Similarly, the SED of IR1525+36 has a much warmer mix of dust with temperatures 26K and 57K in the ratio 15:1, and predicts a flux of 0.06\,mJy at 850\,µm and 0.20\,mJy at 450\,µm. The average stacked 850\,µm and 450\,µm fluxes of 0.44\,mJy and 3.35\,mJy we measure from the 8\,µm Spitzer sources indicates that our stacking is sensitive to borderline ULIRGS. Although ULIRGS would be considered extreme systems in the local universe, at z ~ 1, they are quite the norm (eg. Daddi et al. 2005).

An interesting result is the peak in 450\,µm emission we measure from the 8\,µm sources around z = 1.5. At this wavelength, the energy density of the background is approximately 25% of the maximum at ~ 200\,µm (compared to only 3% at 850\,µm). Given that the 8\,µm sources make up a significant fraction of the 450\,µm background, it would not be unreasonable to expect that the entire far-IR/submm background is dominated by systems around this redshift. This is a slightly lower redshift than the median redshift z = 2.2 of the population of radio detected submm galaxies studied by Chapman et al. (2005). However, the Chapman et al. sample is substantially brighter (by \times 40) on average than the submm galaxies probed by the stacking in our work. This is consistent with the downsizing scenario in which larger galaxies generally form earlier than smaller galaxies. However, this result could be heavily influenced by difficult to quantify, varying selection effects between both studies. Clearly, we must wait for observations with a high 200\,µm sensitivity to provide a complete and definitive answer as to the nature of the far-IR/submm background.

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Fig. 7.— Distribution of submillimeter S/N at the positions of the Spitzer sources (shaded histogram, left ordinates) compared with the distribution of S/N over the entire SCUBA map (open histogram, right ordinates). For the 850µm data, secure $+ \geq 4\sigma$ SCUBA sources are removed and $z > 1.3$ Spitzer sources are selected. No SCUBA sources are removed from the 450µm data and $1 < z < 2$ Spitzer sources are selected.

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