THE CANADA-UK DEEP SUBMILLIMETER SURVEY. VI. THE 3 HOUR FIELD

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ABSTRACT

We present the complete submillimeter data for the Canada-UK Deep Submillimeter Survey (CUDSS) 3h field. The observations were taken with the Submillimeter Common-User Bolometric Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT) on Mauna Kea. The 3h field is one of two main fields in our survey and covers 60 arcmin² to a 3 mJy depth of ~3 mJy. In this field we have detected 27 sources above 3σ and 15 above 3.5σ. We assume that the differential source counts follow the form N(S) ∝ S⁻α and measure α = 3.3±1.4, in good agreement with previous studies. We estimate that SCUBA sources brighter than 3 mJy are responsible for ~13% of the extragalactic background at 850 μm (after correcting for flux boosting, 20% with no correction), which is in general agreement with previous estimates made by other groups. Using preliminary Infrared Space Observatory 15 μm maps and VLA 1.4 GHz data, we have identified counterparts for 10 objects and have detected two sources at 450 μm. With this information we estimate a lower limit on the median redshift of the sample of z > 1.4 with 6%-10% lying at z < 1. We have attempted to measure the angular clustering of S≥50 μm > 3 mJy sources using the source catalogs from the CUDSS two main fields, the 3h and 14h fields, and find ω(θ) = 4.4 ± 2.9θ⁻⁰.⁸, or a 3σ upper limit on the clustering amplitude of less than 8.7 arcsec⁻¹. This is consistent with clustering at least as strong as that seen for the Lyman break galaxy population and the extremely red objects. Since SCUBA sources are selected over a broader range in redshifts than these two populations, the strength of the true spatial clustering is expected to be correspondingly stronger.

Subject headings: cosmology: observations — galaxies: evolution — galaxies: formation — galaxies: high-redshift — submillimeter

1. INTRODUCTION

Over the last decade there have been great steps forward in our understanding of the formation and early evolution of galaxies. There are currently two general, distinct theories of massive galaxy formation, although the true picture is likely a combination of the two. In the first, galaxies form over a range of redshift, from the gradual hierarchical merging of smaller aggregates (Baugh, Cole, & Frenk 1996; Kauffmann & Charlot 1998). In this picture galaxy formation is an ongoing process characterized by star formation rates of moderate magnitude. In the second scenario galaxies form at high redshift on short timescales from the collapse of a single object and undergo one massive burst of star formation (Eggen, Lynden-Bell, & Sandage 1962). They then evolve passively to galaxies of the present day.

The observational picture is still somewhat confused. Many optical and ultraviolet (UV) studies have found that the UV luminosity density of the universe increases out to z ~ 1 (Lilly et al. 1996; Madau, Pozzetti, & Dickinson 1998; Hogg et al. 1998), although Cowie, Songaila, & Barger (1999) have measured a much shallower increase with no obvious peak at z ~ 1. According to the observations of the Lyman break galaxy (LBG) population, the UV luminosity density does not decrease to at least z ~ 4 (Steidel et al. 1999). However, the star formation rates in individual LBGs of a few tens of solar masses per year (Steidel et al. 1996), although large compared to local starbursts, are too moderate to form an elliptical galaxy on a dynamical timescale of ~10⁸ yr and suggest gradual, hierarchical formation. The hierarchical model is further supported by the increase in the rate of galaxy-galaxy interaction with redshift (Patterson et al. 2002).

On the other hand, the spheroids, which contain ~1/3 of the stars in the universe (Fukugita, Hogan, & Peebles 1998), remain old at z ~ 1 (Zepf 1997; Cimatti et al. 1999; Scodberg & Silva 2000; Moriondo, Cimatti, & Daddi 2000). The homogeneous nature of their stellar populations today (Bower, Lucey, & Ellis 1992) implies formation over a short timescale and at high redshift. However, until recently, no high-redshift object with star formation rates large enough to form a massive spheroid in a dynamical timescale had been seen. The deep submillimeter surveys of the last five years (Smail, Ivison, & Blain 1997; Hughes et al. 1998; Barger et al. 1998; Eales et al. 1999, hereafter Paper I) with the Submillimeter Common-User Bolometric Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT) have uncovered just such a population.

The results of these deep SCUBA surveys have been exciting and in general agreement with each other. The population revealed by the SCUBA surveys covers a broad range of redshift, with a median redshift of 2 < z < 3 (Barger et al. 1999b; Smail et al. 2000; Yun & Carilli 2002; Fox et al. 2002; Ivison et al. 2002). Many of the submillimeter detections that have secure optical/near-infrared
(NIR) counterparts show disturbed morphology or multiple components suggestive of galaxy mergers (Lilly et al. 1999, hereafter Paper II; Ivison et al. 2000). These objects have spectral energy distributions (SEDs) broadly similar to today’s ultraluminous infrared galaxy (ULIRG) population. In the local universe the ULIRGs are the most luminous galaxies and emit the bulk of their energy at far-infrared (FIR) wavelengths. The FIR emission is from dust that is currently thought to be heated by young stars (Lutz, Veilleux, & Genzel 1999). The local ULIRGs are primarily the result of mergers and result in objects with surface brightness profiles of elliptical galaxies (for a review see Sanders & Mirabel 1996). Although the dust temperature of the SCUBA sources is very poorly known, if we assume a temperature similar to the local ULIRGs, then these objects are extremely luminous, with bolometric luminosities of $10^{12}$–$10^{13}$ $L_\odot$. Radio and CO observations of a bright SCUBA source (Ivison et al. 2001; cf. Downes & Solomon 2003) have detected possible extended emission, which is in marked difference to the compact nature of local ULIRGs. The CO luminosities of several other SCUBA sources are commensurate with very massive galaxies (Frayer et al. 1998, 1999; Genzel et al. 2003). It is still unclear whether the majority of these objects are powered by star formation or active galactic nuclei (AGNs). Evidence is mounting through X-ray and optical emission line measurements that, although AGNs are present in a fraction of sources, star formation is the dominant process (Ivison et al. 2000; Fabian et al. 2000; Barger et al. 2001). Given this, the SCUBA sources must be forming stars at unprecedented rates of several hundreds to thousands of solar masses per year (Ivison et al. 2000; Paper I). These high star formation rates, coupled with the contribution that these objects make to the total extragalactic background, indicate that this is a cosmologically significant population (Eales et al. 2000, hereafter Paper IV) and make it hard to avoid the conclusion that these objects are elliptical galaxies being seen during their initial burst of star formation.

Analysis of the spatial clustering of different populations can provide clues to their evolutionary connections. Recent measurements of the clustering of two other populations of high-redshift galaxies, the LBGs and extremely red objects (EROs; Giavalisco et al. 1998; Giavalisco & Dickinson 2001; Daddi et al. 2000, 2001), have yielded surprising results. Studies of the $z < 1$ universe (Le Fèvre et al. 1996; Carlberg et al. 2000) have found the clustering strength of galaxies to decrease with increasing redshift, as expected in a scenario in which structure forms through gravitational instabilities. However, the LBGs at $z \sim 3$ and the EROs at $z \gtrsim 1$ are very strongly clustered. With hindsight this result is in agreement with the prediction of Kaiser (1984) that the highest peaks in the density field of the early universe should be strongly clustered. At the redshifts of LBGs and EROs the universe was much younger and there had been less time for gravitational collapse; therefore, these objects are probably the result of the collapse of the rare high peaks in the density field. As SCUBA sources are even rarer than the LBGs and, based on their star formation rates, perhaps more massive, they would also be expected to show clustering.

Peacock et al. (2000) investigated the underlying structure in a submillimeter map of the Hubble Deep Field (HDF; Hughes et al. 1998), after removing all discrete sources above 2 mJy, and found no significant clustering of the underlying flux. However, the HDF area is small and much larger areas are needed to investigate the clustering of submillimeter sources. Of the current deep SCUBA surveys there are three blank-field surveys of significant size and with which a clustering measurement may be attempted: the Borys et al. (2002) map centered on the Hubble Deep Field, the “8 mJy survey” (Scott et al. 2002), and our own, the Canada-UK Deep Submillimeter Survey (CUDSS). Additionally, a deep survey is currently being carried out at 1.2 mm using MAMBO on IRAM, which will cover a square degree (F. Bertoldi et al. 2003, in preparation). The “8 mJy survey” covers an area of 260 arcmin$^2$ with $S_{850\mu m} > 8$ mJy. Their clustering results, although consistent with clustering as strong as seen in the ERO population, are inconclusive. Our survey covers 100 arcmin$^2$ and reaches twice as deep.

This paper is the sixth of a series of papers on the CUDSS project and contains the complete submillimeter data of our 3rd field. The submillimeter survey is now complete, and the final catalog contains 50 sources, 27 of which have been detected in the 3rd field. Paper I introduces the survey and initial detections; Paper II discusses the first optical identifications; Gear et al. (2000, hereafter Paper III) discuss the multiwavelength properties of a particularly interesting and bright source, 14-A; Paper IV presents the nearly complete 14$^2$ field submillimeter sample and discusses the mid-IR and radio properties of the sources; Webb et al. (2003, hereafter Paper V) investigate the relationship between SCUBA sources and LBG galaxies in the CUDSS fields; and D. L. Clements et al. (2003, in preparation, hereafter Paper VII) and T. M. Webb et al. (2003, in preparation, hereafter Paper VIII) will discuss the optical and NIR properties of the entire sample.

This paper is laid out as follows: § 2 describes the submillimeter observations, § 3 discusses the data reduction and analysis techniques, § 4 presents the source catalog, § 5 discusses the radio and Infrared Space Observatory (ISO) data, in § 6 we discuss individual sources, in § 7 we present the source counts, in § 8 the clustering analysis is performed, the implications of these results are discussed in § 9, and in § 10 we present our conclusions.

2. SUBMILLIMETER OBSERVATIONS

We observed 60 arcmin$^2$ of the Canada-France Redshift Survey (CFRS) 3rd field over 25 nights from 1998 January through 2001 July with SCUBA on JCMT (Holland et al. 1999). These data are part of the larger CUDSS, which also includes a 50 arcmin$^2$ region in the CFRS 14$^2$ field and two deep 5.4 arcmin$^2$ regions in the CFRS 10$^2$ and 22$^2$ fields. Some of these observations are discussed in earlier papers (please see § 1 for outline) and will be discussed further in future papers. SCUBA is a system of two bolometeric arrays that observe at 850 and 450 $\mu$m simultaneously. The beam sizes are roughly 14$'$5 and 7$'$5 at 850 and 450 $\mu$m, respectively. Our data were taken using the “jiggle mode” of SCUBA, which fully samples the sky plane through 64 offset positions.

The final image is a mosaic of 101 overlapping individual jiggle maps (~50 minutes per jiggle map). Each point in the final map contains data from nine separate jiggle maps, giving an effective total integration time of about 8 hr. Because a source will likely fall on different bolometers in different jiggle maps, this procedure reduces the chance of spurious sources being produced by noisy bolometers. This
mosaicking procedure also produces a fairly constant level of noise over a large area of sky.

We chose a "chop throw" of 30" so that while chopping off-source an object will still fall on the array, except at the very edges of the map. We chopped in right ascension, which creates a distinct pattern on the map for real objects of a positive source with two negative sources (at half the flux) offset by 30" in right ascension on either side. In the map analysis this pattern is used to discriminate between real sources and spurious noise spikes, which, unlike real objects, will not be accompanied by two negative sources.

The opacity of the atmosphere was determined from "skydip" observations that were taken in between each single jiggle map (approximately once every hour) except in exceptionally stable weather when skydips were taken every second jiggle map. Observations to correct for pointing errors were done with the same frequency, and pointing offsets were consistently less than 2".

The observations were calibrated each night using Mars, Uranus, CRL 618, or IRC +10216. Although IRC +10216 has long-term variability, it was recalibrated in 1998, and the variability is much less than our expected calibration error at 850 µm of approximately 10%. The maps are calibrated such that a 10 mJy point source would produce a peak pixel flux of 10 mJy.

3. DATA REDUCTION AND SOURCE EXTRACTION

The data reduction procedure is discussed in detail in Paper IV. We follow the standard SCUBA User Reduction Facility (SURF) reduction procedure (Jenness 1997). First, the "nod" is removed by subtracting the off-position data from the on-position data. Next, the maps are flat-fielded, which removes the effects of sensitivity variations between the bolometers and adds positional information to the data stream. We then correct for sky opacity using the $T_{850}$ and $T_{450}$ values determined from the skydips taken before and after each observation. The median sky value at each second is determined and removed from all the bolometers. This is done because in practice the chopping and nodding procedure used to remove the sky emission does not work perfectly for two reasons. First, the sky may vary faster than the chop frequency. Second, this procedure will only remove linear gradients in the sky brightness. Individual measurements from the time series of each bolometer above 3 $\sigma$ are then rejected from the data in three iterative steps to reduce the noise. As our objects are faint, even after 8 hr of integration, we are not in danger of removing source flux in this step. The data from individual bolometers are weighted according to their noise and "rebinned" (which includes an intrinsic smoothing of the data) to construct a map. Figure 1 shows our final 850 µm map, smoothed with a 10" Gaussian profile.

The map used for source extraction is produced by convolving the raw rebinned map with a beam template; therefore, the data have been smoothed considerably. The beam template includes the two negative beams as well as the single positive beam and is produced from the observations of our flux calibrators, which are close to being point sources. This suppresses spurious sources (noise spikes) in the final map as they are not well matched to the negative-positive-negative pattern of the beam. Real sources, on the other hand, are well matched to the beam template, and the flux in the negative beams is combined with the positive flux in the final convolved map, thereby increasing the signal-to-noise ratio ($S/N$). This procedure will also produce a more accurate measurement of the position of the source since the positional information left on all three beams is used.

SCUBA acquires data at 450 and 850 µm simultaneously, and so the 450 µm data, although significantly less useful than the 850 µm data because of the increased sky noise and decreased sky transparency, come for free. The 450 µm data were reduced in the same way as the 850 µm data, and the map was convolved with the beam template.

We generated maps of the noise through Monte Carlo simulations, as described in Paper IV. For each jiggle map data set, we determined the standard deviation of the time stream for each bolometer and then replaced the time stream with artificial data with the same standard deviation. We implicitly assumed that the real time stream has a Gaussian distribution and that the noise on different bolometers was uncorrelated.

The artificial time stream does not have quite the same distribution as the real time stream, partly because the reduction procedure removes points more than 3 $\sigma$ from the mean. To simulate this effect, we applied the reduction procedure to the artificial time stream and then rescaled the result so it again had the same standard deviation as the real time stream. As with the data, the final noise maps are convolved with the beam template and therefore are substantially smoothed. The individual, convolved artificial maps have typical noise levels of 1 mJy. We produced 500 simulated maps, and the final noise map (Fig. 1) was generated from the standard deviation of each pixel in these maps.

As a result of varying weather conditions, our 3º map is not as uniformly sampled as our 14º map (Paper III), which is clearly visible in Figure 1. Most striking is the single deep pointing (27 across) that was taken in early 1998. The noisy edge effects are also seen and a well-understood effect of SCUBA's mapping technique. The center strip of the map was observed during excellent conditions, the top and bottom strips were observed under marginal conditions, and the top strip also has less time coverage. Ignoring the noisy edge, the beam-convolved map may be broken into three general sections, listed as follows (it should be noted that these flux levels are given in mJy beam$^{-1}$, where our beam has been smoothed by the beam template, to roughly 20" FWHM):

1. The central deep pointing: mean 1 $\sigma$ noise = 0.77 mJy.
2. The central strip: mean 1 $\sigma$ noise = 1.1 mJy.
3. The top and bottom strips: mean 1 $\sigma$ noise = 1.4 mJy.

4. THE CATALOG

The source extraction was performed on the map that had been convolved with the beam template. We produced an S/N map by simply dividing this map by the noise map. The extraction procedure is complicated because not only do many of the peaks in the map have low S/N, but they are also sometimes merged together. To get a better measurement of both the flux and position of a source, we used the iterative deconvolution (CLEANing) technique described in Paper IV to compile a source catalog.

Because we are working at low S/N, near the confusion limit, the data reduction, source extraction, and noise analysis were performed separately and in parallel by the Cardiff and Toronto groups and the final source lists compared.
Sources were included in the catalog if their Cardiff-Toronto average S/N was above 3. The complete 3h catalog is presented in Tables 1 and 2. There are 27 objects in total that were detected above 3. Sources that were less than 3 in one of the maps (but averaged above 3) are noted. Also listed are offsets in the Cardiff-Toronto averaged recovered positions. In Paper IV we showed that with our source extraction technique we were 90% complete to 3 mJy. We have not attempted to model the effects of merging these two catalogs on completeness because the two catalogs are in good agreement, with no systematic offsets in flux or position. The differences in individual flux
measurements are, on average, less than 0.5 mJy, well within the measurement error. There are five sources at less than 3.5 \( \sigma \) that were detected at less than 3 \( \sigma \) in one of the two catalogs (although with \( \geq 3 \sigma \) when averaged between the two).

Gaussian statistics predict approximately one spurious detection for every 300 beams, or approximately four sources for our map. These would be symmetric around zero, and we would therefore expect approximately two positive spurious sources. However, because the combined effect of the beam shape, confusion, and noise is clearly very complicated, the simulated maps and an analysis of the negative sources are the best tools for analyzing the reliability of the catalog. In Paper IV we showed that the contamination rate from false detections on simulated maps was comparable to the beam shape, confusion, and noise is clearly very complicated. When averaged between the two). Since the noise is symmetric around zero, the number of peaks in the inverted real map produces a similar result. Since the noise is symmetric around zero, the number of peaks in the inverted real map, above a given S/N, will be indicative of the number of spurious positive sources. This number becomes large below 3 \( \sigma \). Above the 3 \( \sigma \) threshold there are two negative sources (both less than 3.5 \( \sigma \)), indicating that about this number of our positive detections are spurious, again consistent with the prediction of Gaussian statistics. It should be noted that this analysis was done after the CLEANing procedure was completed and all the positive sources had been removed from the map. Before this, there were negative sources at greater than 3 \( \sigma \), which were the off-beams of real positive sources, and these should not be included in the analysis.

In Paper IV we showed that our extraction technique, when applied to simulated data, recovered the correct slope

| Name       | R.A.          | Decl.       | S/N | \( S_{850 \mu m} \) (mJy) | \( S_{450 \mu m} \) (3 \( \sigma \) upper limits) | Positional Offset (Cardiff-Toronto) |
|------------|---------------|-------------|-----|--------------------------|----------------------------------------|-----------------------------------|
| CUDSS 3.1  | 03 02 44.55   | 00 06 34.5  | 7.4 | 10.6 \( \pm \) 1.4       | 83 \( \pm \) 26 (6.3) \(^a\)            | 1.8                               |
| CUDSS 3.2  | 03 02 42.80   | 00 08 1.50  | 6.7 | 4.8 \( \pm \) 0.7        | 197                                     | 1.0                               |
| CUDSS 3.3  | 03 02 31.15   | 00 08 13.5  | 6.4 | 6.7 \( \pm \) 1.0        | 197                                     | 1.0                               |
| CUDSS 3.4  | 03 02 44.40   | 00 08 55.0  | 6.2 | 8.0 \( \pm \) 1.3        | 197                                     | 1.0                               |
| CUDSS 3.5  | 03 02 44.40   | 00 08 11.5  | 5.8 | 4.3 \( \pm \) 0.7        | 197                                     | 1.0                               |
| CUDSS 3.6  | 03 02 36.10   | 00 08 17.5  | 5.4 | 3.4 \( \pm \) 0.6        | 197                                     | 1.0                               |
| CUDSS 3.7  | 03 02 35.75   | 00 08 11.0  | 5.3 | 8.2 \( \pm \) 1.5        | 197                                     | 1.0                               |
| CUDSS 3.8  | 03 02 26.55   | 00 08 19.0  | 5.0 | 7.9 \( \pm \) 1.6        | 197                                     | 1.0                               |
| CUDSS 3.9  | 03 02 28.90   | 00 10 19.0  | 4.6 | 5.4 \( \pm \) 1.2        | 76.9 \( \pm \) 25 (0) \(^a\)            | 1.0                               |
| CUDSS 3.10 | 03 02 52.50   | 00 08 57.5  | 4.5 | 4.9 \( \pm \) 1.1        | 197                                     | 1.0                               |
| CUDSS 3.11 | 03 02 52.90   | 00 10 22.0  | 4.0 | 5.0 \( \pm \) 1.3        | 197                                     | 1.0                               |
| CUDSS 3.12 | 03 02 38.70   | 00 10 26.0  | 4.0 | 4.8 \( \pm \) 1.2        | 197                                     | 1.0                               |
| CUDSS 3.13 | 03 02 35.80   | 00 09 53.5  | 3.8 | 4.1 \( \pm \) 1.1        | 197                                     | 1.0                               |
| CUDSS 3.14 | 03 02 25.78   | 00 09 7.50  | 3.5 | 5.1 \( \pm \) 1.5        | 197                                     | 1.0                               |
| CUDSS 3.15 | 03 02 27.60   | 00 06 52.5  | 3.5 | 4.4 \( \pm \) 1.3        | 197                                     | 1.0                               |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

\(^a\) In parentheses is the offset in arcseconds between the 850 \( \mu m \) peak and the 450 \( \mu m \) peak.
of the source counts slope, although the measured flux density of the individual sources was boosted by a factor of approximately 1.44. One might expect the number of false detections to increase because of flux boosting, but this should not be a significant effect. The flux boosting of real sources is the result of the combined effect of a real source and the noise and the fact that we search for the peak flux. That is, for each real source, when convolving with the beam, the recovered flux and position are biased toward positive noise spikes on top of the profile, rather than negative. A spurious source is simply the result of a noise spike convolved with the beam template and is not boosted in this way.

We define two catalog lists: the primary list containing 15 objects above 3.5 \( \sigma \), which we regard as secure sources, and the secondary list containing 12 objects between 3.5 and 3.0 \( \sigma \), which are more dubious. Based on the above reasoning, we expect approximately two objects in the secondary list to be false detections.

Also listed in Tables 1 and 2 are the 450 \( \mu \)m flux measurements and 3 \( \sigma \) upper limits for each source, measured at the 850 \( \mu \)m position on the 450 \( \mu \)m map. We searched for 450 \( \mu \)m flux in two ways. First, we used the 450 \( \mu \)m map that had been convolved with the beam and searched for greater than 3 \( \sigma \) peaks within the error radius (\( \sim 8'' \)) of the 850 \( \mu \)m position. This gave us a list of possible 450 \( \mu \)m detections. To test the robustness of these detections, we performed aperture photometry on the unconvolved map as in Dunne & Eales (2001). Sources that had consistent flux measurements from both these methods (i.e., consistent within their 1 \( \sigma \) errors) were taken as real detections. There were two such sources corresponding to sources 3.1 and 3.9. This is consistent with the 450 \( \mu \)m number counts of other groups (Blain et al. 1999a, 2002; Smail et al. 2002). Although the 450 and 850 \( \mu \)m positions may be significantly offset from each other (e.g., Ivison et al. 2000), the smaller beam of the JCMT at 450 \( \mu \)m (7'' FWHM) means that the position of the 450 \( \mu \)m peak flux is expected to be a better estimate of the true position of the source than at 850 \( \mu \)m.

### 5. THE RADIO AND ISO IDENTIFICATIONS

We have obtained a VLA map of the entire field at 1.4 GHz with the B configuration (M. Yun et al. 2003, in preparation), and the data were reduced following the technique outlined in Ivison et al. (2002). These data reach a 1 \( \sigma \) depth of 11 \( \mu \)Jy, and we have searched for submillimeter counterparts within 8'' and above 3.6 \( \mu \)Jy (or 40 \( \mu \)Jy). The ISO data consist of a preliminary list of 15 \( \mu \)m objects from Flores and collaborators (H. Flores et al. 2003, in preparation).

To identify possible associations between the SCUBA sources and ISO and radio objects, we use the same positional probability analysis we have used in earlier papers for the optical and NIR data (Paper II). The probability that an unrelated ISO or radio source will lie within a distance \( r \) of a given SCUBA position can be described by

\[
P = 1 - \exp(-nr^2),
\]

where \( n \) is the surface density of the ISO or radio sources. Our Monte Carlo analysis (Paper IV) indicates that the true position of a SCUBA source will lie within 8'' of the measured position 90\%–95\% of the time; therefore, we have chosen this distance to be our nominal search radius. Because the surface densities of ISO and radio sources are small, we do not expect many chance associations even with such a large search radius. The one exception to this is an area within our field with an exceptionally high surface density of ISO sources. For the SCUBA sources that lie in this area we have used the increased surface density to calculate \( P \). The results are given in Tables 3 and 4.

The source with the largest \( P \)-value determined from the radio data is CUDSS 3.8, as a result of the very large offset of 9'' between the radio position and the SCUBA position. In a sample of this size, we would expect about one source to have an identification with such a \( P \)-value, purely as a result of chance coincidence. However, this \( P \)-value is likely an overestimate. This object is very bright (at all wavelengths), and objects of its brightness (or brighter) have a lower surface density than the general radio population, which was used to estimate \( P \). Therefore, it has a much lower probability of being found close to a SCUBA source randomly. The other objects with radio detections have such smaller \( P \)-values, and we may regard them as secure identifications.

For the six sources with ISO detections CUDSS 3.8 is also the least secure, again because of its large offset from the submillimeter position. Source CUDSS 3.27 would also be an insecure identification based only on its ISO detection; however, it has a supporting radio detection as well. Given the \( P \)-values of the remaining four ISO identifications, we would expect less than one chance coincidence within this group; therefore, we regard these identifications as secure.

Based on Monte Carlo simulations of the SCUBA data (Paper IV), we expect \( \sim 20\% \) of the identifications to be offset from the SCUBA position by greater than 6''. Looking

### TABLE 3

| Name       | 1.4 GHz Flux (\( \mu \)Jy) | Offset to SCUBA Position (arcsec) | \( P \)       | Notes                |
|------------|--------------------------|----------------------------------|-------------|----------------------|
| CUDSS 3.6  | 43 ± 12                  | 0.95                             | 0.00056     | Unresolved           |
| CUDSS 3.7  | 44 ± 12                  | 2.3                              | 0.0032      | Unresolved           |
| CUDSS 3.8  | 735 ± 23                 | 9.0                              | 0.05        | Extended 0.73        |
| CUDSS 3.10 | 154 ± 34                 | 1.3                              | 0.0011      | Extended 2.1         |
| CUDSS 3.15 | 226 ± 12                 | 2.3                              | 0.0032      | Unresolved           |
| CUDSS 3.17 | 104 ± 37                 | 2.4                              | 0.036       | Extended 2.1         |
| CUDSS 3.24 | 122 ± 32                 | 3.6                              | 0.008       | Extended 2.2         |
| CUDSS 3.25 | 377 ± 57                 | 7.0                              | 0.031       | Unresolved           |
| CUDSS 3.27 | 49 ± 12                  | 4.0                              | 0.01        | Unresolved           |

\* The given flux is the peak flux if the source is unresolved and the total flux if the source is extended.
first at the nine radio identifications, the fraction of identifications at offsets larger than this is 22%, which is certainly consistent with the expected fraction. The fraction of ISO identifications with offsets greater than 6\" is 50% and, although we are dealing with small number statistics, may imply that some of the identifications at larger offsets are incorrect. However, two of these identifications are also detected at 1.4 GHz. For the remaining ISO identification, source 3.22, we cannot say with any certainty whether this object has been correctly identified. Based only on its P-value, we would randomly expect 0–1 sources with identifications at this level of significance.

6. NOTES ON INDIVIDUAL SOURCES

Below we discuss individual sources with detections at ISO, radio, and 450 \( \mu m \) wavelengths and sources with Cardiff-Toronto positional offsets of greater than 2\". The optical and NIR identifications of these sources are discussed in detail in Paper VII. We work in AB magnitudes and colors, and the conversion to the Vega system is as follows: \( K_{AB} = K_{Vega} + 1.78 \) and \( (I-K)_{AB} = (I-K)_{Vega} - 1.3 \).

6.1. CUDSS 3.1

This is the brightest object in both the 3\textsuperscript{rd} and 14\textsuperscript{th} catalogs. It is detected at 450 \( \mu m \), which would suggest that it lies at low redshift. This agrees with a possible optical identification, CFRS 03.0982 (Paper VII), which has a spectroscopically determined redshift of \( z = 0.1952 \) (Hammer et al. 1995). This source is located near the edge of the field and is highly confused with CUDSS 3.4 as well as a third possible 850 \( \mu m \) source at less than 3 \( \sigma \), making the position uncertain. The new 450 \( \mu m \) position increases the offset to CFRS 03.0982 from 4\" to 7\", but even with this larger offset it remains the best available optical/NIR identification.

However, there are two facts that suggest that this is not the correct identification. First, the probability (based on its optical properties) that CFRS 03.0982 is unrelated to the SCUBA source is quite large (Paper VII). Second, if this object does indeed have a redshift of \( z = 0.1951 \), it should certainly be detected at 1.4 GHz, given its 450 and 850 \( \mu m \) fluxes, which it is not. This source is discussed in further detail in Paper VII, but for now we assume that CFRS 03.0982 is not the correct identification.

6.2. CUDSS 3.6

This source has been detected at 1.4 GHz at an offset of 1\" and has an NIR counterpart with \( K_{AB} = 23.2 \pm 1.0 \) and \( (I-K)_{AB} > 1.7 \) (Paper VII).

6.3. CUDSS 3.7

This source has been detected at 1.4 GHz at an offset of 2\". The NIR image shows a quartet of compact very red objects and EROs, discussed in detail in Paper VII. All are within ~2\" from each other, the reddest of which is coincident with the radio position and has \( K_{AB} = 22.1 \pm 0.1 \) and \( (I-K)_{AB} = 2.9 \pm 0.4 \).

6.4. CUDSS 3.8

This source is detected at 1.4 GHz and 15 \( \mu m \) with ISO (ISO 1003). The most obvious optical counterpart, CFRS 03.0358, has a spectroscopic redshift of \( z = 0.0880 \) (Hammer et al. 1995). The identification offset of 9\" is the largest for our sample, but the radio and ISO detections and clear merger morphology in the optical image (Paper VII) make the identification more secure. There is no 450 \( \mu m \) detection, but this is not entirely surprising since the object lies very near the edge of the smaller 450 \( \mu m \) map where the noise increases rapidly.

6.5. CUDSS 3.9

This object is one of two detected at 450 \( \mu m \), which suggests that it lies at low redshift. However, there is no galaxy visible within 8\" of the SCUBA position in deep optical and NIR images to \( K_{AB} \sim 22.5 \) and \( I_{AB} \sim 25.0 \).

6.6. CUDSS 3.10

This object is detected at 1.4 GHz and identified with ISO 425 with an offset of 1\". The optical image shows a very bright galaxy (CFRS 03.1299, \( I_{AB} = 19.4 \)) with clear merger morphology. It has a spectroscopic redshift of \( z = 0.176 \) (Hammer et al. 1995).

6.7. CUDSS 3.13

The Toronto-Cardiff positions disagree by 3\'2. This source appears extended and may therefore be two confused sources.

6.8. CUDSS 3.15

This source has been detected at 1.4 GHz and 15 \( \mu m \) (ISO 1040) with an offset of 2\" from the submillimeter position. The most obvious optical identification, CFRS 03.0346, is a bright \( (I_{AB} = 22.1) \) galaxy with \( (I-K)_{AB} = 2.1 \pm 0.1 \). The \( I \)-band \textit{Hubble Space Telescope} image of this source shows extremely interesting morphology (discussed in detail in Paper VII). It has a similar morphology to a collisional ring galaxy, with a central bright, compact source, surrounded by a ringlike structure. This morphology is very similar to two other potential SCUBA counterparts (Smail et al. 2002; 2003).

### TABLE 4

| CUDSS Name | ISO Name | \( S_{15\mu m} \) (mJy) | Offset to SCUBA Position (arcsec) | \( P \) |
|------------|---------|-----------------|--------------------------|------|
| CUDSS 3.8  | ISO 1003| 1480 ± 200      | 9.6                      | 0.22 |
| CUDSS 3.10 | ISO 425 | 825 ± 160       | 1.5                      | 0.00087 |
| CUDSS 3.15 | ISO 1040| 254 ± 96        | 3.2                      | 0.027 |
| CUDSS 3.22 | ISO 770 | 335 ± 90        | 7.5                      | 0.021 |
| CUDSS 3.24 | ISO 382 | 181 ± 90        | 2.1                      | 0.0017 |
| CUDSS 3.27 | ISO 1039| 174 ± 92        | 6.7                      | 0.11 |
Ivison et al. 2002), both at redshifts of ~1 (S. C. Chapman et al. 2003, in preparation). The $S_{1.4\text{GHz}}/S_{850\mu m}$ redshift estimate places it at $z = 0.7 \pm 0.4$.

6.9. **CUDSS 3.16**

This is a faint source, and the Toronto-Cardiff positions disagree by 3''.

6.10. **CUDSS 3.17**

This source has been detected at 1.4 GHz but has no optical or NIR counterpart to our detection limits ($K_{AB} \sim 23$ and $I_{AB} \sim 26$). The radio data indicate that the radio emission is extended over 2''.

6.11. **CUDSS 3.22**

This is identified with ISO 770. The position of the ISO source lies directly in between two possible optical identifications, both of which are discussed in Paper VII. The first is CFRS 03.1029, a bright optical galaxy ($I_{AB} = 21.1$) with $(I-K)_{AB} = 1.5$. It is resolved and has simple spheroidal morphology. The second candidate, which is the more convincing identification, is a faint, red galaxy ($I_{AB} \lesssim 24.5$) with $(I-K)_{AB} \approx 3.0$ and is 1'' closer to the ISO position.

6.12. **CUDSS 3.23**

The Toronto-Cardiff positions disagree by 3''. This object is near the edge of the map, where the noise increases rapidly, and is below 3 $\sigma$ in one of the Toronto-Cardiff catalogs.

6.13. **CUDSS 3.24**

This source is very close to the edge of the map and has a Toronto-Cardiff positional disagreement of 3''. It is identified at 1.4 GHz and is also ISO 382. The radio emission is extended over 2''. The ISO and radio positions are coincident with an optically faint ($I_{AB} \gtrsim 24.0$), red ($[I-K]_{AB} \approx 3.0$) galaxy.

6.14. **CUDSS 3.25**

This source has a radio counterpart offset 7'' from the SCUBA position. There is a faint optical source at this position, with $I_{AB} = 24.1$ and $(I-K)_{AB} = 1.8$.

6.15. **CUDSS 3.27**

The Toronto-Cardiff positional disagreement for this source is 3'' (the largest disagreement in the catalog), which is not surprising since this source is the faintest of a trio of confused sources including CUDSS 3.15 and CUDSS 3.8. This object is detected at 1.4 GHz and is coincident with ISO 1039. Note that all three sources in this trio of SCUBA sources are identified with ISO sources and are detected in our radio map. There is an apparent optical counterpart for this object with $I_{AB} = 23.4$ and $(I-K)_{AB} = 1.5$, although this is offset from the radio position by 3'', with the ISO position lying between the two.

7. THE SOURCE COUNTS

In this section we present the integral source counts from these data and the data from the 14th field in Figure 2 (without a correction for flux boosting). They are in good agreement with the results of other surveys (Barger, Cowie, & Sanders 1999b; Blain et al. 1999a, 1999b; Borys et al. 2002; Scott et al. 2002). To fit the counts, we assumed that the form $N(> S) = N_0 S^{-\alpha}$ and used the maximum likelihood technique outlined in Crawford, Jauncey, & Murdoch (1970) to determine $\alpha$. We find for the combined sample $\alpha = 3.5^{+1.1}_{-1.4}$ for the differential counts [$N(S) \propto S^{-\alpha}$], where the errors are 95% confidence limits. As mentioned in § 4, in Paper IV we investigated the effects of confusion and noise on the source counts and concluded that the slope is unaffected, although the counts are shifted upward through flux boosting.

Although we know that a small fraction of our objects are spurious, it is not possible to remove the effect of this contamination since it is not possible to know which sources they are, nor which flux levels to correct. The false detections are likely objects detected at less than 3.5 $\sigma$, and we can see from Table 2 that these sources span a range in flux levels from 2.8 to 5.8 mJy and are therefore not restricted to a single flux bin. However, we expect only approximately two false detections, and so the most likely effect will be an increase of the counts in one of our bins by two points, which will not change our source count slope.

We have included four new sources from the 14th field that were not part of the catalog presented in Paper IV. These four sources were detected with new data that were obtained for the 14th field after the publication of Paper IV. These new data complete the observations of the 14th field, and the sources themselves are discussed in more detail in Paper VIII. We note that there was a programming error in the source count analysis of the 14th field in Paper IV that led to an incorrect area determination, but this did not significantly change the measurement of $\alpha$ and did not alter the main conclusions.

The conclusion of Paper IV that SCUBA sources brighter than $S_{850\mu m} > 2$ mJy contribute ~20% to the background (before correcting for the flux boosting effect) at 850 $\mu m$ is unchanged by these new data and the new analysis.
Correcting for the flux boosting effect reduces this fraction to 13\%, or roughly 7\% of the total extragalactic background light. This is in good agreement with the results of many other workers (Barger et al. 1999a; Hughes et al. 1998; Blain et al. 1999a, 1999b; Cowie, Barger, & Kneib 2002; Smail et al. 2002). It should be noted that the estimates of other groups have not been corrected for flux boosting due to confusion, although this effect will apply to all surveys whose mapping and source extraction techniques are similar to this work.

8. THE ANGULAR DISTRIBUTION OF SCUBA SOURCES

We measured the angular correlation function for the SCUBA sources in the two fields, largely following the procedure given in Roche & Eales (1999). To estimate $\omega(\theta)$, we used the Landy & Szalay (1993) formalism:

$$\omega(\theta) = \frac{DD - 2DR + RR}{RR}$$

where $DD$ is the number of SCUBA pairs at a given separation $\theta$, $DR$ is the number of SCUBA-random pairs, and $RR$ is the number of random-random pairs, all normalized to the same number of objects. The Landy & Szalay (1993) approach is believed to have good statistical properties when a small correlation is expected.

To form $DR$ and $DD$, a sample of 5000 artificial SCUBA sources was generated, carefully taking into account sensitivity variations in the images. To do this, we generated a set of random positions on the assumption of uniform sensitivity across the map. We then randomly assigned fluxes to these positions using the best power-law fit to the source counts (§ 7). Using the noise maps (§ 3; see also Paper IV), we determined whether each artificial source would be detected at greater than 3 $\sigma$ and thereby modeled the variation in source density across the SCUBA images.

The correlation analysis is further complicated by the shape of the beam. There will be no sources within $\sim 17''$ of one another since at this distance objects will be confused. However, the effect of the beam actually extends over separations of $\sim 50''$ in the right ascension direction (but not in declination) as a result of the chop, and in this region around a given source we are less likely to detect another source. We have attempted to correct for this through our CLEANing algorithm, but the effect of the beam can only partially be removed. To take account of this in the clustering analysis, we placed masks around each SCUBA source corresponding to the shape of the beam. The number density of random sources around each SCUBA source thus more properly reflects the data. We calculated $\omega(\theta)$ for the entire sample as well as separately for each field.

One might wonder if flux boosting has an effect on this analysis. In the simplest scenario, where we have an average flux boosting of a factor of 1.44, uniform across our map and invariant with inherent source flux, it should have no effect. At the faint end it may cause some sources to fall out of or be boosted into our sample, but this uncertainty is expected even without flux boosting. However, the flux boosting effect is caused by both noise and confusion from fainter objects and consequently will be spatially correlated. For example, a varying noise level across the map could create the appearance of clustering for a randomly distributed input sample. We have attempted to correct for this when generating the background random objects; furthermore, in our maps we see no evidence that the noise is varying to such a high degree that this is an important effect. Moreover, the clustering seen in the 3h field is lower than for the 14h field, although its noise is less uniform. In regions of high confusion the magnitude of the flux boosting may increase, and so, assuming that the faint objects trace the same structure as the bright sources, this underlying population would work to increase the clustering signal. However, as we are attempting to measure an average clustering strength for a range of SCUBA flux levels, this effect does not introduce false clustering but essentially extends our flux limit below 3 mJy.

A final complication in the clustering calculation is that of the ‘integral constraint.’ If $\omega(\theta)$ is estimated from an image, the integral

$$\frac{1}{\Omega^2} \int \omega_{est}(\theta) d\Omega_1 d\Omega_2$$

will necessarily be zero, even though the same integral of the true correlation function will not be zero for any realistic image size (Groth & Peebles 1977). As in Roche & Eales (1999), we assumed that the observed angular correlation is given by

$$\omega(\theta) = A (\theta^{-0.8} - C)$$

and $C$ is calculated from

$$C = \sum N_{rr}(\theta) \theta^{-0.8} \sum N_{rr}(\theta),$$

where $N_{rr}$ is the number of random-random pairs. For the 14h and 3h fields we measure this to be 0.0106 and 0.0104, respectively.

Figure 3 shows our estimates of $\omega(\theta)$ for both the 3h and the 14h field and the combined results where the errors are estimated following Hewett (1982):

$$\delta \omega(\theta)^2 = \frac{1 + \omega(\theta)}{N_p},$$

where $N_p$ is the number of pairs in each bin.

Fitting the data for the amplitude, we measure $A = 2.4 \pm 4.0$ arcsec$^{0.8}$ for the 3h field, $A = 6.6 \pm 4.2$ arcsec$^{0.8}$ for the 14h field, and $A = 4.4 \pm 2.9$ arcsec$^{0.8}$ for the combined data. As this measurement is significant at less than 2 $\sigma$, it is also useful to quote a 3 $\sigma$ upper limit for the amplitude of $\leq 8.7$ arcsec$^{0.8}$. These two fields are small enough that variance from field to field is expected to be important, and so some discrepancy between the 3h and 14h fields is expected, although their measured amplitudes are consistent within the large uncertainties. It should be noted, however, that the 14h field, in which we have a 1.5 $\sigma$ measurement, has very uniform noise properties (as a result of excellent weather). There is no clustering signal in the 3h field, which has variations in sensitivity across the map that are more extreme than for the 14h field. Although we have attempted to correct for this, it may have washed out any clustering signal that was present in the 3h field.

Any effects due to the beam or chopping procedure that have not properly been removed will effect the innermost bin in Figure 3 (at separations less than 45''). The clustering signal at this separation is larger than for all other separations, although the uncertainty is also significantly larger. If
2 as the observed circles correspond to the 14 h field, the filled circles correspond to the 3 h field, and the open triangles correspond to the two fields combined. The solid line is the angular correlation function fit to the combined data, the dashed line is the angular correlation function of LBGs (Giavalisco et al. 1998; \( \omega(\theta) = 20^{-0.9} \)), and the dotted line is the angular correlation function of EROS (Daddi et al. 2000; \( \omega(\theta) = 5.80^{-0.8} \)).

Clustering information could, in principle, be gained from the difference in the number density of the two fields. The fractional error for the integral source counts for both fields is smallest for sources with flux densities greater than 3.5 mJy. We estimated the true surface density of objects from the average surface density of sources in the two fields. Using this value, the difference in the number counts of the two fields is within the shot noise and is not indicative of clustering. Still, it does not rule it out since with such small field sizes shot noise is expected to dominate.

9. DISCUSSION

9.1. The Nature and Redshift Distribution of SCUBA Sources

Determining the redshift distribution of the SCUBA population has proven difficult for two reasons: (1) determining the optical/NIR counterpart is not trivial because of the large beam size of the JCMT at 850 \( \mu \)m, and (2) the inherent faintness of these sources at optical and NIR wavelengths makes spectroscopy difficult. Consequently, photometric redshift estimates, using a range of wavelengths, offer the best alternative. For the sources presented in this paper we have spectroscopic redshifts for two out of 27, and the 450 \( \mu \)m, 1.4 GHz, and ISO data provide further redshift information.

The 450 \( \mu \)m/850 \( \mu \)m flux ratio can be used as a rough redshift estimate, although it is highly dependent on the shape of the SED. In Figure 4 we show the 450 \( \mu \)m/850 \( \mu \)m flux ratios for these objects as a function of redshift. We include the 450 \( \mu \)m detections from the 3h and 14h fields and upper limits from the 3h field only. The optical counterparts of sources 3.8 and 3.10 have spectroscopic redshifts from the CFRS. For the remaining sources the redshift, or redshift lower limit, has been estimated from the radio data (Carilli & Yun 1999, 2000; Dunne, Clements, & Eales 2000).

Overlaid are the SEDs of three template galaxies. The solid line corresponds to Arp 220, the archetypal local ULIRG, the dashed line to a reddened starburst galaxy (which has less extinction than a ULIRG), and the dotted line to the more extreme object, IRAS 10214+4724. To estimate the reddened starburst SED, we used the tabulated values of Schmitt et al. (1997) and extended the spectrum to wavelengths larger than 60 \( \mu \)m assuming a dust temperature of 48 K and a dust emissivity index of 1.3, a good fit to the starburst galaxy M82. For IRAS 10214+4724 we assumed a temperature of 80 K and a dust emissivity index of 2 (Downes et al. 1992).

The 450 \( \mu \)m/850 \( \mu \)m ratio for all three galaxy types drops very rapidly beyond a redshift of \( z \sim 1-2 \) as the observed 450 \( \mu \)m flux approaches the peak of the thermal flux. Thus, a detection at 450 \( \mu \)m is indicative of either a low-redshift or very bright object. However, the ratio is highly dependent on temperature and the dust emissivity index and therefore, in the absence of SED information, loses its power as a precise redshift indicator.

In Paper IV we found that the \( S_{450,\mu m}/S_{850,\mu m} \) upper limits for the 14h field sources were consistent with all three template galaxies. For the sources in the 3h field with estimated redshifts \( z > 1 \) and \( S_{450,\mu m}/S_{850,\mu m} \) upper limits we find a similar result, except for source 3.9, which has an...
also shown for two sources, estimated from their nondetection at 1.4 GHz. The fluxes at 850 μm have been corrected for flux boosting effects. Overlaid are the SEDs for Arp 200 and a dusty starburst galaxy. The objects with spectroscopic redshifts are denoted by open circles, and those with radio estimated redshifts are denoted by filled circles. Redshift lower limits are also shown for two sources, estimated from their nondetection at 1.4 GHz.

![Diagram](image)

**Fig. 5.** —15 μm/850 μm flux ratio as a function of redshift for the sources with 15 μm identifications (six in the 3rd field and three in the 14th field). The fluxes at 850 μm have been corrected for flux boosting effects. Overlaid are the SEDs for Arp 200 and a dusty starburst galaxy. The objects with spectroscopic redshifts are denoted by open circles, and those with radio estimated redshifts are denoted by filled circles. Redshift lower limits are also shown for two sources, estimated from their nondetection at 1.4 GHz.

excessively high $S_{\text{850 μm}}/S_{\text{850 μm}}$ ratio, given its redshift lower limit. As in Paper IV, we measure the mean 450 μm/850 μm flux ratio from the mean 450 μm flux of all sources in the catalog and find a 3 σ upper limit of $S_{\text{850 μm}}/S_{\text{850 μm}} = 2.6$. This is considerably lower than for those objects detected at 450 μm (which were included in the estimate) and is most consistent with SEDs similar to Arp 200 and the dusty starburst at redshifts of $z > 2$.

We have detected six sources at 15 μm with ISO, and all but source 3.22 are also detected in the radio. The 15 μm/850 μm flux ratio is a much stronger function of redshift than the 450 μm/850 μm ratio (Fig. 5) beyond $z \sim 0.5$ but is also highly SED dependent. For sources 3.8 and 3.10, which have spectroscopic redshifts, the $S_{\text{15 μm}}/S_{\text{850 μm}}$ ratio is lower than found for both the dusty starburst and Arp 200. However, the remaining four ISO detections appear to have higher ratios than expected for these SEDs if they lie at redshifts greater than $z > 3$. At $1.0 < z < 3.0$ they are consistent with both Arp 200 and a dusty starburst.

The redshift information is listed in Table 5. The redshift lower limits are derived from the radio/submillimeter flux ratio relation (Barger et al. 1999a; Dunne et al. 2000; Carilli & Yun 2000) and a nondetection of the source at 1.4 GHz. The 850 μm measurements have been corrected assuming the average flux boost of a factor of 1.44. This will give a better estimate of the redshift distribution although for any individual source the flux correction is uncertain by ±1.2 (the 1 σ scatter about the average flux boosting factor).

We do not have a sufficient number of redshift measurements to estimate a meaningful median redshift for this population, but assuming that all redshifts lie at their low limit, we may estimate a lower limit for the median redshift. Using the 3rd data and the previously published 14th field data (Paper IV), we estimate a median redshift of $z > 1.4$. Note that the originally published redshift estimates and lower limits in Paper IV had not been corrected for the flux boosting effect as they have been here. This result is in agreement with the general consensus in the literature that the bulk of the sources lie at $z > 1$ with a median redshift $z \sim 2–3$ (Barger et al. 1999b; Smail et al. 2000, 2002; Fox et al. 2002; Ivison et al. 2002).

Our radio detection limit is such that a typical galaxy in the SLUG survey (the template galaxies for this redshift estimator; Dunne et al. 2000) will drop out of our sample at $z \sim 1.5$, therefore making it difficult to estimate the fraction of sources that lie below $z = 2$. However, 6%–10% of the objects in our complete catalog (the 3rd and 14th fields from Paper IV) are currently identified with $z < 1$ (6% from the spectroscopic redshift measurements and 10% when the radio redshift estimates are included). This fraction of sources below $z \sim 1$ is already equal to the prediction of Blain et al. (1999c) that 10% of the $S_{\text{850 μm}} > 2$ mJy population will lie below $z = 1.7–2.4$.

The fraction of the SCUBA population that lies at low redshift ($z < 1$) is currently a contentious issue as a number of original low-redshift identifications by other groups (Smail et al. 1998; Chapman et al. 2002; Dunlop et al. 2002) have proven to be incorrect, and the real counterpart is a faint, high-redshift object. Gravitational lensing may offer an explanation for the apparent overabundance of low-redshift identifications in our own survey (Blain 1996, 1998; Chapman et al. 2002). In this scenario the majority of the low-redshift identifications are not the true counterparts to

| Name    | Redshift Estimate$^a$ | Spectroscopic Redshift |
|---------|-----------------------|------------------------|
| CUDSS 3.1 | >2.3 (0.5)            | ...                    |
| CUDSS 3.2 | >1.6 (0.4)            | ...                    |
| CUDSS 3.3 | >1.9 (0.4)            | ...                    |
| CUDSS 3.4 | >2.0 (0.5)            | ...                    |
| CUDSS 3.5 | >1.5 (0.4)            | ...                    |
| CUDSS 3.6 | 1.3 ± 0.3             | ...                    |
| CUDSS 3.7 | 2.0 ± 0.4             | ...                    |
| CUDSS 3.8 | 0.3 ± 0.1             | 0.0880                 |
| CUDSS 3.9 | >1.7 (0.4)            | ...                    |
| CUDSS 3.10 | 0.8 ± 0.2             | 0.176                  |
| CUDSS 3.11 | >1.6 (0.4)            | ...                    |
| CUDSS 3.12 | >1.6 (0.4)            | ...                    |
| CUDSS 3.13 | >1.5 (0.4)            | ...                    |
| CUDSS 3.14 | >1.6 (0.4)            | ...                    |
| CUDSS 3.15 | 0.6 ± 0.2             | ...                    |
| CUDSS 3.16 | >1.2 (0.3)            | ...                    |
| CUDSS 3.17 | 1.1 ± 0.3             | ...                    |
| CUDSS 3.18 | >1.5 (0.4)            | ...                    |
| CUDSS 3.19 | >1.4 (0.3)            | ...                    |
| CUDSS 3.20 | >1.4 (0.3)            | ...                    |
| CUDSS 3.21 | >1.5 (0.4)            | ...                    |
| CUDSS 3.22 | >1.3 (0.3)            | ...                    |
| CUDSS 3.23 | >1.7 (0.4)            | ...                    |
| CUDSS 3.24 | 1.0 ± 0.3             | ...                    |
| CUDSS 3.25 | 0.3 ± 0.1             | ...                    |
| CUDSS 3.26 | >1.4 (0.3)            | ...                    |
| CUDSS 3.27 | >1.3 ± 0.3            | ...                    |

$^a$ The most probable $S_{\text{450 μm}}/S_{\text{850 μm}}$ redshift estimate or lower limit. The number in parentheses is the error associated with the estimate (or lower limit) from Dunne & Eales 2001. The error in the redshift estimate due to the 1 σ uncertainty in the flux is roughly ±0.1–0.2 for all objects. All 850 μm flux measurements have been corrected for flux boosting.
the submillimeter sources but are foreground galaxies acting as gravitational lenses. A striking example of this effect is source HDF 850.1, which Dunlop et al. (2002) have convincingly shown has been lensed by a foreground galaxy, originally identified as the counterpart.

It is certainly possible that lensing has affected the identifications in this paper. However, in the case of HDF 850.1 the radio-to-submillimeter redshift estimate of \( z \sim 4 \) was in clear disagreement with the low-redshift identification. In our own case, four of the low-redshift identifications that have radio detections (3.8, 3.10, 3.15, 3.25) have radio-to-submillimeter redshift estimates that place them at \( z < 1 \). Therefore, regardless of the redshift of the possible optical counterpart, these four objects (8% of the catalog) appear to lie below \( z \sim 1 \). This conclusion is obviously based on two assumptions. The first is that the radio and submillimeter emission is indeed coming from the same objects, as we claimed in § 5. These radio identifications are secure, in particular those of sources 3.10 and 3.15, which have small (<4") positional offsets from their submillimeter positions.

We have also assumed that the radio-to-submillimeter redshift estimator, which is empirically based on low-redshift star-forming galaxies, may be uniformly applied at all redshifts without the introduction of significant uncertainty. Clearly, if this is not the case (see Blain, Barnard, & Chapman 2003), it would be incorrect to indiscriminately apply this estimator to these objects.

All of the sources detected in the shallower “8 mJy survey” (Fox et al. 2002; Ivison et al. 2002) appear to lie at \( z > 1 \). Granato et al. (2001) predict that the brighter submillimeter population (\( S_{850} > 10 \) mJy) will have a narrower redshift distribution than the fainter population (\( S_{850} > 1 \) mJy), and we may be seeing this effect. Ivison et al. (2002) have reported tentative evidence for luminosity evolution, such that submillimeter luminosity increases with redshift. However, with small numbers in both our survey and the 8 mJy survey and the dearth of spectroscopically confirmed redshifts, there is no strong discrepancy between these two results.

The high-redshift regime (\( z > 3 \)) is potentially the most interesting for discriminating between different structure formation models. However, because of the difficulty in redshift estimates at larger distances, the number of submillimeter sources that lie at \( z > 3 \) is still an unknown quantity. The data of Smail et al. (2002) indicate a median redshift of \( z = 2.6_{-1.4}^{+1.9} \) but are consistent with half of their sources lying above \( z \sim 3 \). Recently, Ivison et al. (2002) have reported a median redshift \( \geq 2.6 \). Thus, the literature is converging on a median redshift of \( z \sim 2-3 \). With a lack of confirmed redshifts it is impossible for us to estimate a median redshift, but as we have detected two sources at 450 \( \mu m \) and five (possibly six) at 15 \( \mu m \), we can make the rough claim that at least 30% of this sample lies below \( z \sim 3 \).

### 9.2. Clustering of High-Redshift Dusty Galaxies

Structure formation theory holds that the objects that form from the highest peaks in the density field of the early universe will be strongly clustered (Kaiser 1984). Indeed, studies of the star-forming LBG population, at redshifts \( z \sim 3-4 \), have revealed strong spatial clustering (Giavalisco et al. 1998), implying that they formed in the most massive dark halos. At low redshift, clustering strength is strongly correlated with morphology by early-type galaxies more clustered than late-type galaxies by a factor of \( \sim 3 \) (Shepherd et al. 2001). At \( z \sim 1 \), the EROs are very clustered, with \( r_0 = 12 \pm 3 \) h\(^{-1}\) Mpc (Daddi et al. 2001). EROs are an inhomogeneous mixture of early-type galaxies and dusty starbursts, with the majority believed to be massive early-type galaxies (Stiavelli & Truè 2001; Moriondo et al. 2000). Thus, if the objects discovered with SCUBA are progenitors of massive spheroidal galaxies, we expect them to be clustered as well.

Overlaid on Figure 3 are the angular correlation functions derived for LBGs by Giavalisco & Dickinson (2001) and for EROs by Daddi et al. (2000). For the EROs we have plotted the correlation function for the faintest sample in Table 5 of Daddi et al. (2000). Our results are consistent with the angular clustering of SCUBA sources being as strong as for either of these populations.

However, if the angular clustering strengths of the three populations are the same, their spatial correlation functions will have different amplitudes because of their different redshift distributions. It is difficult to model this accurately because, although the redshifts of LBGs are tightly constrained, the redshift distributions of the SCUBA sources and of the EROs are very uncertain. It is likely, however, that this effect will depress the angular correlation function of the SCUBA sources relative to the other populations since they are expected to have the widest redshift distribution.

The spatial clustering strength of the SCUBA sources may be estimated by assuming a redshift distribution for the population and following the procedure outlined in Efstathiou et al. (1991; see also Infante & Pritchet 1995; McCracken et al. 2000). If the angular correlation function follows the form

\[
\omega(\theta) = A\theta^{1-\gamma},
\]

then the correlation length of the spatial clustering is related to the angular correlation amplitude, \( A \), by

\[
A \sim C r_0^{-1},
\]

where \( C \) contains the effects of cosmology and redshift distribution (Efstathiou et al. 1991). It should be noted that, as we have assumed \( \gamma = 1.8 \) with no error, this results in a measurement of spatial clustering of higher statistical significance than the angular clustering. The significance of the result should be taken from the angular clustering uncertainty.

Dunlop (2001) has summarized the current redshift results in the literature and estimates a mean redshift for the SCUBA sources of \( z \sim 3 \) with \( \pm 10\% \) of the sources at \( z < 1 \). We therefore take the redshift distribution to have a Gaussian form, centered at \( z = 3 \) and with a standard deviation of \( \Delta z = 0.8 \).

Adopting an \( \Omega_m = 0.3 \) and \( \Omega_\Lambda = 0.7 \) cosmology, we find, for the combined sample,

\[
r_0 = 12.8 \pm 4.5 \pm 3.0 \, h^{-1} \text{Mpc}.
\]

The first error is statistical and is estimated from \( \omega(\theta) \) and \( \Delta \omega(\theta) \). As \( \omega_0 \sim r_0^\gamma \) and we have fixed \( \gamma = 1.8 \), a given uncertainty in \( r_0 \) corresponds to a much larger uncertainty in \( \theta_0 \). Thus, the largest uncertainty in \( r_0 \) comes from the uncertainty in the slope of the correlation function and is not included in our quoted error. The second error is systematic and has been estimated by varying the redshift distribution parameters: \( \tau = 2.5-3.5 \) and \( \Delta z = 0.6-1.1 \). (The apparent higher statistical significance of this result is
caused by the fact that we have assumed a value for the slope of the correlation function, rather than trying to determine it from the data. The significance of our result should be taken from our angular clustering result.)

This value is comparable to the $r_0 = 12 \pm 3$ h$^{-1}$ Mpc found by Daddi et al. (2001) for EROs but larger than measured for the LBGs, although the uncertainties are substantial. Giavalisco & Dickinson (2001) found values of $r_0$ ranging from 1.0 to 5.0 (with an error of $\sim 1.0$ for all) for different UV flux–limited Lyman break samples. The 3 $\sigma$ upper limit on the angular clustering is consistent with the SCUBA sources being as strongly clustered angularly as the LBGs and possibly more clustered spatially given their different redshift distributions. If SCUBA sources are as clustered as LBGs, this would suggest that they also formed in massive and rare dark matter halos in the early universe.

Magliocchetti et al. (2001) have predicted that the SCUBA sources will be more clustered than the LBGs. Using a model first presented in Granato et al. (2001), they suggest that SCUBA sources and LBGs are both progenitors of QSOs. In this picture LBGs represent the lower luminosity, lower mass end and SCUBA sources the higher luminosity, higher mass end of the same population. They predict the spatial clustering of SCUBA sources to be greater than that of LBGs and that the clustering strength should increase with submillimeter flux. At about 100" they predict $\omega(\theta) \sim 0.006-0.02$ for $M_{\text{halo}}/M_{\text{ph}} = 10-100$, respectively, for sources with $S_{850} > 1$ mJy. This is much smaller than we could detect with our small numbers but also much smaller than our measured value of $\omega(100") = 0.11 \pm 0.07$ (from our best-fit function).

We do not have a large enough area to test the prediction that clustering strength should increase with submillimeter luminosity, since the surface density of SCUBA sources drops rapidly with increasing flux, and we therefore have only a small number of bright submillimeter objects. Scott et al. (2002) have attempted to measure the clustering of the brighter $S_{850} > 8$ mJy sources over a larger area, and ideally a comparison between the clustering strength of objects in our fainter sample and the objects in their survey might lead us to an answer. However, their measurement of clustering was inconclusive, and the small numbers of both our samples make it impossible to determine if there is indeed a relationship between clustering strength and luminosity for these objects.

10. CONCLUSIONS

We have used SCUBA on the JCMT to map 60 arcmin$^2$ of the CFRS 3 h field. We have detected 27 sources, bringing the final number of objects at $S_{850,\mu m} \geq 3$ mJy detected in the CUDSS to 50. We have found the following results:

1. For the differential source counts $[N(S) \propto S^{-\alpha}]$ we measure $\alpha = 3.3^{+0.4}_{-0.5}$, which is in excellent agreement with other studies. Down to 3 mJy these objects are responsible for $\sim 13\%$ of the 850 $\mu$m background energy.

2. We have used preliminary ISO 15 $\mu$m data, VLA 1.4 GHz observations, and SCUBA 450 $\mu$m maps to identify counterparts of the 850 $\mu$m sources. Using spectroscopy from the CFRS and the radio-to-submillimeter redshift estimator (Carilli & Yun 1999; Dunne et al. 2000), we measured a lower limit on the mean redshift of the population of greater than 1.4, with 6%-10% of the objects below $z < 1$.

3. We have attempted to measure the angular clustering of $S_{850} > 3$ mJy sources using the complete CUDSS 3 h and 14 h catalogs. We find $\omega(\theta) = 4.4 \pm 2.9 \theta^{-0.8}$, or a 3 $\sigma$ upper limit of $A \leq 8.7$ arcsec$^{-0.8}$. This is as strong as the angular clustering measured for LBGs and EROs, and the spatial clustering will be even stronger as a result of the broad redshift range of SCUBA sources compared to LBGs and EROs.

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