

THE CANADA–UNITED KINGDOM DEEP SUBMILLIMETER SURVEY. V. THE SUBMILLIMETER PROPERTIES OF LYMAN BREAK GALAXIES

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ABSTRACT

We have used 850 μm maps obtained as part of the Canada–UK Deep Submillimeter Survey (CUDSS) to investigate the submillimeter properties of Lyman break galaxies (LBGs). We used three samples of LBGs: two from the Canada–France Deep Fields (CFDF) survey covering CUDSS 14 and CUDSS 03, and one from Steidel and collaborators also covering CUDSS 14. We measure a mean flux from both CFDF LBG samples at a level of $\sim 2\sigma$ of 0.414 ± 0.263 mJy for CUDSS 03 and 0.382 ± 0.206 mJy for CUDSS 14, but the Steidel et al. sample is consistent with zero flux. From this we place upper limits on the Lyman break contribution to the 850 μm background of $\sim 20\%$. We have also measured the cross-clustering between the LBGs and the SCUBA sources. From this measurement we infer a large clustering amplitude of $r_0 = 11.5 \pm 3.0 \pm 3.0 h^{-1}$ Mpc for the Steidel et al. sample (where the first error is statistical and the second systematic), $r_0 = 4.5 \pm 7.0 \pm 5.0 h^{-1}$ Mpc for CFDF 14, and $r_0 = 7.5 \pm 7.0 \pm 5.0 h^{-1}$ Mpc for CFDF 03. The Steidel et al. sample, for which we have the most significant detection of clustering, is also the largest of the three samples and has spectroscopically confirmed redshifts

Subject headings: cosmology: observations — dust, extinction — galaxies: evolution — galaxies: formation — galaxies: starburst — submillimeter

1. INTRODUCTION

Recent work at optical and submillimeter wavelengths has granted us unprecedented access to the high-redshift universe. In particular, the Lyman break selection technique (Steidel & Hamilton 1993) has provided thousands of star-forming galaxies at redshifts $z \sim 3$ and 4. These data, and the results of other optical surveys (Lilly et al. 1996; Madau et al. 1998; Hogg et al. 1998), have shown that the global star formation rate (SFR; inferred from the UV luminosity density at different redshifts), increases with redshift to $z \sim 1$ and may remain constant to at least $z \sim 4$ (Sawicki, Lin, & Yee 1997; Steidel et al. 1999), implying the beginning of the epoch of galaxy formation occurred at $z \gg 1$.

Studies of the spatial distribution of Lyman break galaxies (LBGs) show that they are highly clustered even at these early redshifts (Giavalisco et al. 1998). This was initially unexpected since the clustering of galaxies had been shown to decrease with redshift to $z \sim 1$ (Carlberg et al. 1997; Le Fèvre et al. 1996) in line with theoretical predictions, but the strong clustering of LBGs is actually a natural consequence of the effects of bias. Kaiser (1984) showed that the high peaks of the density distribution in the early universe will have been highly clustered, and so objects that

form from these high peaks, clusters at a redshift of zero or galaxies at a redshift of 3, should also be highly clustered.

The high SFRs ($50\text{--}100 M_{\odot} \text{ yr}^{-1}$) and comoving density of the LBGs make them attractive progenitors of present-day elliptical galaxies (Pettini et al. 1998), although their masses are still highly uncertain (Sawicki & Yee 1998; Somerville, Primack, & Faber 2001). However, the Submillimeter Common-User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT) has revealed a population of dusty galaxies with implied SFRs of greater than $300 M_{\odot} \text{ yr}^{-1}$ (Smail, Ivison, & Blain 1997; Hughes et al. 1998; Eales et al. 1999). The redshifts of these objects are still highly uncertain, with estimates of the median redshift of the population lying between 2 and 3 (Eales et al. 2000; Barger et al. 1999; Smail et al. 2000; Yun & Carilli 2002; Fox et al. 2002). They have similar spectral energy distributions to today's ultraluminous infrared galaxies (ULIRGs) and often show disturbed morphology or multiple components, implying they may be the result of galaxy mergers (Lilly et al. 1999; Ivison et al. 2000). Both LBGs and SCUBA sources have sufficient SFRs to form present-day elliptical galaxies but the extremely high SFRs of the latter mean this can be done on the order of 10^8 yr, as the homogeneous properties of local elliptical galaxies indicate is the case.

The nature of the relationship between these two populations remains unclear. An obvious scenario is one in which they form a continuum of objects with the bright submillimeter-selected sources representing the highest star-forming LBGs. Adelberger & Steidel (2000) claim that by assuming an $L_{\text{bol, dust}}/L_{\text{UV}}$ typical of normal starbursts, the LBG population can produce the bulk of the 850 μm background. In this picture the two populations are the same objects, and a separate population of highly obscured ULIRG-like objects is not needed. The ratio of optical to submillimeter emission for the brighter SCUBA sources is,

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however, much less than for the starbursts considered by Adelberger & Steidel, and so these objects almost certainly represent a separate population (Gear et al. 2000; Eales et al. 2000; Downes et al. 1999), but it is unclear whether the fainter SCUBA sources, with $S_{850} < 3$ mJy, overlap with the LBG population.

Various optical techniques have been used to infer the dust content of LBGs. Pettini et al. (2001) have used optical line ratios, and Shapley et al. (2001) fitted the predictions of star formation models to optical and near-IR photometry. Both have concluded that the most intrinsically luminous LBGs, which have higher SFRs, contain more dust. However, a more reliable way of measuring the dust content is directly through submillimeter photometry. Chapman et al. (2000) have used SCUBA to observe a sample of high-SFR LBGs, and they estimate that the 850 μm flux density is at least 2 times lower than predicted from UV colors. Using the submillimeter map of the Hubble Deep Field (HDF), Peacock et al. (2000) statistically detected the submillimeter flux of galaxies with high UV luminosities and, thus, high SFRs. They detect a higher mean flux of 0.2 ± 0.04 mJy (for galaxies with an inferred SFR of $1 h^{-2} M_{\odot} \text{yr}^{-1}$).

This paper examines the relationship between LBGs and SCUBA sources in two Canada-UK Deep Submillimeter Survey (CUDSS) fields and is organized as follows. Section 2 describes the submillimeter and optical/UV data. In § 3 we investigate the submillimeter fluxes of LBGs. Section 4 discusses the dust properties of LBGs that can be inferred from the results in § 3. In § 5 the correlation function between the two populations is presented. In § 6 we discuss the results and their implications.

2. THE DATA

We have mapped two areas within the Canada-France Redshift Survey (CFRS) fields, CFRS 03+00 and CFRS 14+52, using SCUBA at 850 μm . This study was designed to be a blank-field survey for submillimeter-selected sources above 3 mJy but also produces statistical information for objects below this flux. Each map is roughly 6×8 arcmin² and is a mosaic of single jiggle maps. The submillimeter data and the goals and results of the CUDSS are discussed in detail in Eales et al. (1999, 2000), Lilly et al. (1999), Gear et al. (2000), Webb et al. (2002), T. M. Webb et al. (2003, in preparation), and D. L. Clements et al. (2003, in preparation).

Surveys for Lyman break galaxies have been performed over both these areas. In the 14 hr field (CFRS 14+52) we have access to Lyman break data from two separate sources, the Canada-France Deep Fields (CFDF) survey (McCracken et al. 2001; S. Foucaud et al. 2003, in preparation) and Charles Steidel and collaborators (C. Steidel et al. 2001, private communication). The Steidel et al. list contains 86 galaxies within the SCUBA map area, and most of these have spectroscopically confirmed redshifts. It is an \mathcal{R} -limited survey with $\mathcal{R} < 25.5$ (see Steidel & Hamilton 1993 for discussion of the filter system) and is roughly 0.5 mag deeper than the CFDF data.

The CFDF survey, and in particular the construction of catalogs and limiting magnitudes, is described in detail in McCracken et al. (2001). Details of the CFDF Lyman break selection technique are found in S. Foucaud et al. (2003, in preparation). The survey is I -limited with $I_{\text{AB}} < 24.5$ and has selected galaxies over the redshift range $2.9 < z < 3.5$.

An additional constraint of $(V-I)_{\text{AB}} < 1.0$ has been introduced, which reduces contamination by stars and elliptical galaxies at $z \sim 1.5$. The CFDF team estimate (from simulations) the contamination due to stars to be at the 5% level and that due to galaxies below $z \sim 2.9$ to be 15%. The total level of contamination of 20% is comparable to that of the Steidel sample. In the redshift range of $2.9 < z < 3.5$ and with $I_{\text{AB}} < 24.5$, the CFDF method recovers 70% of the Steidel et al. catalog. Of the entire CFDF survey a subset of 26 galaxies fall within our 14 hr SCUBA area and 29 within the 3 hr field area.

3. SUBMILLIMETER FLUX OF LYMAN BREAK GALAXIES

3.1. Statistical Results

The CUDSS's large, contiguous maps provide a unique opportunity to statistically study the submillimeter flux of a relatively large number of LBGs. Our method is simple: we measure the submillimeter flux at each LBG position in the SCUBA maps and take a weighted mean of these data, obtaining the weights from the noise maps for each field (see Eales et al. 2000; Webb et al. 2002). For high signal-to-noise ratio (S/N) measurements one would measure the flux at the peak of the beam (or the point-spread function), but as these objects are all below the noise level, we cannot locate the peak and must use the value at the LBG location (which will be, on average, offset from the peak, as discussed below). As we will show, it is quite crucial to first remove all sources from the maps that are definitely not associated with an LBG.

Simulations in an earlier paper (Eales et al. 2000) of the submillimeter data have shown that the offset in our maps between the actual position of an object and its recovered position (for the $S_{850\mu\text{m}} > 3$ mJy) is usually within 6'' with the peak of the distribution occurring at approximately 3'' (also see Hogg 2001 for discussion of offsets). The recovered position lies farther than 8'' in only 5%–10% of cases, and so we removed all SCUBA sources from the maps for which there was no LBG within 8''.

For the 3 hr field we removed all of the SCUBA sources; for the Steidel 14 hr sample, all but three sources; and for CFDF 14, all but one source. These four sources are listed in Table 1 along with their identification probability. The source removal, or ‘‘cleaning’’ (discussed in Eales et al. 2000), includes the removal of the entire beam template. That is, not only is the positive flux from a source removed, but so is the negative flux due to the chop. This step is vital since the beam profile, convolved with a point source, essentially extends over greater than 75'' in R.A. and can therefore interfere in flux measurements of nearby sources if not removed.

TABLE 1
LYMAN BREAK GALAXIES WITH $S_{850\mu\text{m}} > 3$ mJy

Source Name	$S_{850\mu\text{m}}$ (mJy)	LBG Name	P Probabilities
CFRS 14–6	4.2	CFDF 64601	0.019
CFRS 14–7	3.2	Steidel West2-MD13	0.096
CFRS 14–8	3.4	Steidel MMD75	0.081
CFRS 14–10.....	3.5	Steidel MMD63	0.072

TABLE 2
SUBMILLIMETER FLUX OF LYMAN BREAK GALAXIES

LBG Sample	Mean Flux ^a	K-S Significance (%)	Mean Flux ^b
CFRS 03+00 CFDF	0.414 ± 0.263	94.4	-0.171 ± 0.263
CFRS 14+52 CFDF	0.382 ± 0.206	88.7	0.760 ± 0.206
CFRS 14+52 Steidel	0.0141 ± 0.110	18.4	-0.021 ± 0.110

^a Submillimeter sources removed.

^b No sources removed.

We determined the probabilities that these four associations are simply chance coincidences in the following way. If an LBG lies a distance d from a SCUBA source, the probability that it is unrelated to the SCUBA source is $P = 1 - \exp(-\pi n d^2)$, where n is the surface density of LBGs (the more sophisticated analysis that takes account of the magnitudes of galaxies is described in T. M. Webb et al. 2003, in preparation). The probabilities, which are given in Table 2, are not particularly low, and so the associations may not be genuine; but because they *might* be genuine, we cannot remove these sources from the maps.

We can use the fact that four LBGs do lie within $8''$ of a SCUBA source to estimate how many real SCUBA-LBG associations we may have missed by discarding all SCUBA sources at a greater distance from an LBG. On the assumption that these four are genuine associations, we would expect, from the results of the simulations, that $(0.05-0.1) \times 4$ associations to have an offset of greater than $8''$. Since some of these four associations are undoubtedly due to random chance, this gives an upper limit of 0.2–0.4 missed identifications.

After removing all the sources except the above, we measured the noise-weighted mean of the flux at the positions of LBGs, treating these three samples of LBGs separately. The results are summarized in Table 2. For each sample, the mean flux is above zero, but clearly not at a very convincing level. The significance of these measurements can be estimated using a simple Kolmogorov-Smirnov (K-S) test that determines the level at which the distribution of LBG fluxes is inconsistent with being drawn randomly from the distribution of pixel values in the submillimeter map. The K-S probabilities are given in Table 2. There are detections at approximately 2σ (K-S probability $\approx 90\%$) for the two CFDF samples, while the Steidel LBG sample is consistent with zero mean flux. The distributions of submillimeter fluxes values for the three LBG samples are shown in Figure 1.

We have also investigated the effect on our analysis if we do not remove any sources from the maps. In this case, we obtain the following results for the three samples: -0.171 ± 0.263 mJy for CFDF 03, 0.760 ± 0.206 mJy for CFDF 14, and -0.021 ± 0.110 mJy for the Steidel 14 hr sample. For the CFDF 14 sample, we now have a highly significant result, while for the other two fields the mean flux has decreased. It may seem counterintuitive that the co-added flux could actually decrease if the bright submillimeter sources are not removed, but this is simply a result of the beam profile. The chopping technique creates two *negative* sources for every positive source (offset by $30''$ in each direction of R.A.) and so if these are not removed, they can lead to a decrease in the co-added flux (especially if the LBGs are

clustered around the bright submillimeter sources). Of course, not removing bright sources can also lead to an increase in the co-added flux, as in the case for the 14 hr CFDF sample, if a significant number of the LBGs are close to the peak of the positive beam (although still with a greater than $8''$ offset).

3.2. The Lyman Break Galaxy Contribution to the Submillimeter Background

The contribution from LBGs to the FIR/submillimeter background (Fixsen et al. 1998) is still an open question and one that can be addressed by these data. The bright submillimeter-selected sources ($S_{850 \mu\text{m}} > 3$ mJy) produce 20%–30% of the background energy at $850 \mu\text{m}$ (Barger et al. 1998, 1999; Hughes et al. 1998; Blain et al. 1999; Eales et al. 2000; Cowie, Barger, & Kneib 2002; Smail et al. 2002), and therefore if the LBGs are the same population as the $S_{850 \mu\text{m}} < 3$ mJy objects, they could be responsible for the remaining 70%–80%. Adelberger & Steidel (2000) estimate that UV-selected galaxies with $m_{1600} < 27$ could easily have produced $\sim 75\%$ of the submillimeter background at $850 \mu\text{m}$. However, in this picture, the bulk of this energy is emitted by LBGs too faint to be included in our optical sample and at submillimeter fluxes too faint to be statistically detected using our method. Chapman et al. (2000), who targeted brighter LBGs ($\mathcal{R} < 24.5$) that are expected to be stronger submillimeter emitters, concluded that these objects produce a negligible contribution to the background.

Given that none of our three LBG samples has been strongly detected as a population at $850 \mu\text{m}$, we estimate upper limits to the background contribution that these galaxies make at this wavelength. Given the 1σ standard error of the co-added flux measurements in Table 1 we can estimate a 3σ upper limit for the background contribution. For the CFDF samples in the redshift range $2.9 < z < 3.5$, the 3 hr field contributes less than 3.2% to the background and the 14 hr field contributes less than 2.8%. For the Steidel et al. sample, which is selected over a larger redshift range of $2.4 < z < 3.4$, the contribution is less than 5.1%.

However, because of the negative K -correction, the observed $850 \mu\text{m}$ flux is constant with redshift (for approximately $0.5 < z < 6$, depending on cosmology), and the contribution of LBGs to the submillimeter background is coming from a wide range of redshifts, not just the tight range over which the Lyman break technique selects galaxies. To determine the total contribution we must include the submillimeter flux from LBGs outside the selected redshift range. To do this we assume that LBGs have a constant comoving number density between redshifts 1 and 5, and then, by integrating the comoving volume increment (dV_c/dz) over this range, we can scale the background contribution accordingly. Thus, upper limits on the total contribution to the background at $850 \mu\text{m}$ become less than 20% for CFDF 03, less than 16% for CFDF 14, and less than 19% for the deeper Steidel et al. sample in the 14 hr field.

3.3. Lyman Break Galaxies Identified with SCUBA Sources

The optical and near-IR counterparts to the greater than 3 mJy SCUBA sources are discussed in detail in T. M. Webb et al. (2003, in preparation) and D. L. Clements et al. (2003, in preparation), along with the identification process. There are four SCUBA sources whose best identification is an

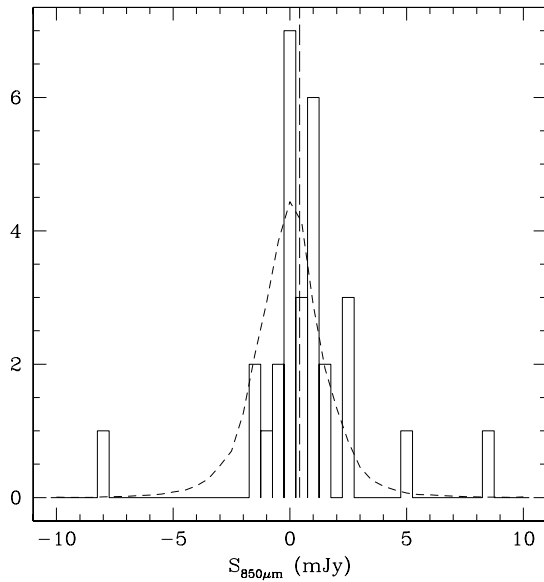


FIG. 1a

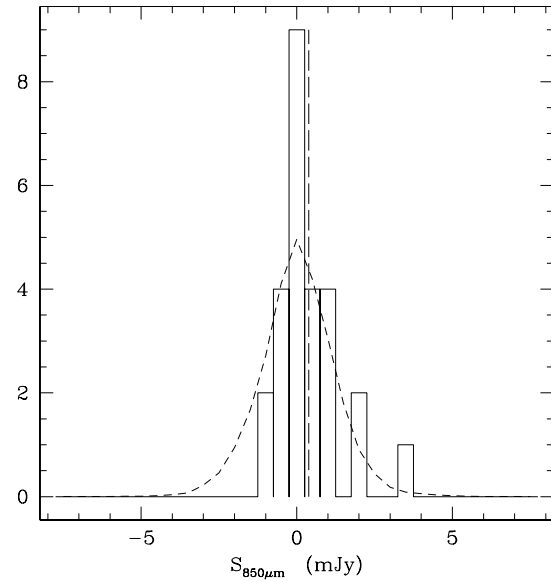


FIG. 1b

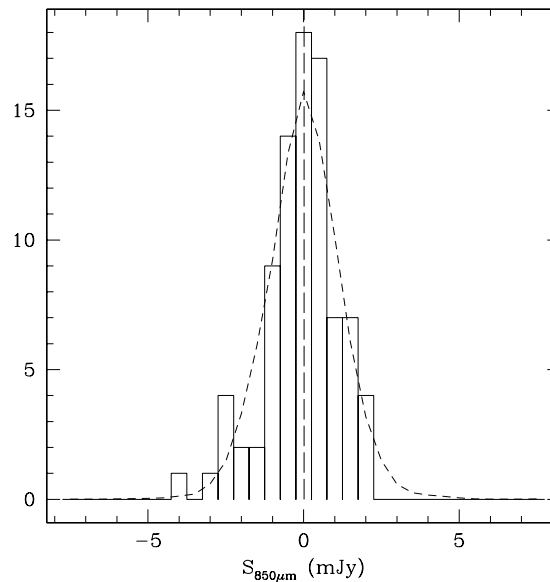


FIG. 1c

FIG. 1.—(a) Submillimeter flux distribution for the LBGs in the 3 hr sample. Overlaid is the distribution of all the pixel values in the 3 hr submillimeter map (with all sources removed) to illustrate the flux levels at which the LBG flux distribution deviates from that of the submillimeter map. The weighted mean of the sample is also shown (*vertical dashed line*). The submillimeter 3 hr field had poorer weather than the 14 hr field and is therefore noisier. The two measurements at greater than 5 mJy and one at less than -5 mJy are in extremely noisy regions of the image (with S/N less than 3σ) and as such have a very low weighting factor in the mean. (b) Same as (a), but for the LBGs in the 14 hr CFDF sample. Overlaid is the distribution of all the pixel values in the 14 hr submillimeter map (with all sources but the one source in Table 2 removed). The weighted mean (*vertical line*) is also shown. (c) Same as (a), but for the LBGs in the Steidel-14 sample. Overlaid is the distribution of all the pixel values in the 14 hr submillimeter map (with all sources but the three listed in Table 2 removed). For consistency, the flux for each object was taken to be the flux at the position of the LBG, including the three LBGs possibly associated with SCUBA objects at greater than 3σ . These three objects have submillimeter fluxes (measured at their submillimeter location) of less than 3.5 mJy and therefore, because of the offset between the LBG and SCUBA positions, have recovered fluxes of ~ 2 mJy.

LBG, three in Steidel et al.'s sample, and one from CFDF 14.

It is interesting to note that the three SCUBA sources identified with Steidel et al. objects are part of a chainlike structure in the submillimeter map and are all within $40''$ of each other. The remaining source, associated with an object in the CFDF 14 sample (but not present in the Steidel et al. sample) is also found in the same general area approximately $1'$ to the west.

West2-MD13, which is identified with 14.7, is the only object of the three possible Steidel LBG identifications with a spectroscopic redshift. This object is a quasar that lies in the largest single overdensity within the redshift range to which the Steidel et al. survey was sensitive. There is reason to expect that SCUBA sources might be associated with overdense regions in the early universe (see § 6). For example, Chapman et al. (2001b) observed an overdensity of LBGs at $z = 3.09$ (Steidel et al. 1998)

with SCUBA and detected a correspondingly high surface density of submillimeter sources.

4. DUST PROPERTIES OF LYMAN BREAK GALAXIES

We have obtained an upper limit (2σ) of $\simeq 0.4$ mJy on the average $850\ \mu\text{m}$ flux of LBGs for both CFDF samples. We converted this to an upper limit on the dust mass using the formula (Hildebrand 1983)

$$M_d = \frac{(1+z)D^2 S_{\text{obs}}}{\kappa_d(\nu_{\text{em}})B(\nu_{\text{em}}, T_d)}, \quad (1)$$

where $(1+z)D$ is the luminosity distance and S_{obs} is the flux. We assumed that all the LBGs are at a redshift of 3, which means that the emitted frequency, ν_{em} , is 1.41×10^{12} Hz, equivalent to $212.5\ \mu\text{m}$. We assumed that the dust mass opacity coefficient, $\kappa_d(\nu)$, has a value of $0.077\ \text{m}^2\ \text{kg}^{-1}$ at $850\ \mu\text{m}$ and extrapolated this to the shorter wavelength using the formula $\kappa_d(\nu) \propto \nu^\beta$ with a dust-emissivity index, β , of 2, for which there is now strong evidence (Dunne & Eales 2001 and references therein). To compare this upper limit with the dust masses of nearby galaxies, we also calculated dust masses for the 104 galaxies in the SCUBA local universe and galaxy survey (SLUGS; Dunne et al. 2000) using the same formula. This survey contains a variety of galaxy types, from ULIRGs like Arp 220 to galaxies that are much more typical of the normal galaxy population. To avoid the uncertainty in β making the comparison between the high- and low-redshift galaxies dubious, we used the multiwavelength data that exists for the SLUGS galaxies to estimate the fluxes of the galaxies at the same frequency used for the LBGs. Therefore, even if the value of β we have assumed to calculate the dust mass opacity coefficient is incorrect, the relative dust masses of the Lyman break and SLUGS galaxies will be correct. The value of the dust mass opacity coefficient at any frequency is still quite uncertain (Alton et al. 2000), and so our absolute dust masses may not be correct, but again our comparison of the dust masses of low- and high-redshift galaxies will be valid, as long as the properties of dust are not radically different at low and high redshift (Eales & Edmunds 1996).

Since the emitted frequency for the LBGs is fairly close to the peak of the dust spectral energy distribution, our dust mass estimates are much more sensitive to the assumed dust temperature than at lower frequencies. Dunne & Eales (2001) have recently shown that for the SLUGS galaxies, the mass-weighted temperature of the dust (the correct one to use in the formula above) is relatively low, even for extreme ULIRGs like Arp 220. They derive an average mass-weighted temperature for the sample of 21.3 ± 0.5 K. We have used this value to derive the dust masses for the LBGs and the individual values of mass-weighted temperature for the SLUGS galaxies. Figure 2 shows the results for the three different cosmologies. Although the mass limit for the LBGs depends quite strongly on the cosmological model, it is clear that their dust masses must be no larger than those of nearby galaxies. The significance of these dust masses will be discussed by L. Dunne et al. (2003, in preparation).

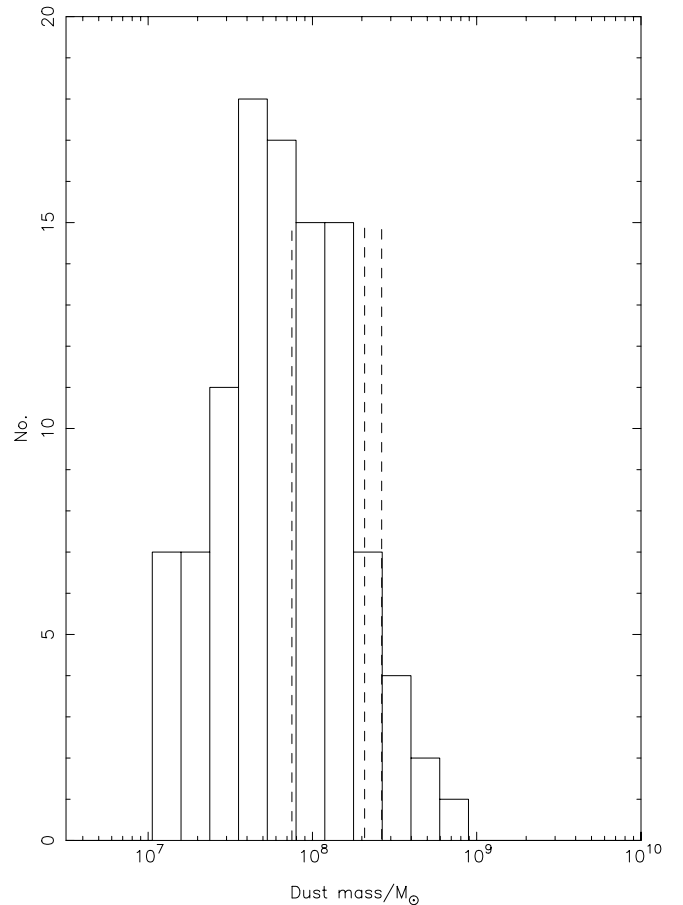


FIG. 2.—Histogram of the dust masses of galaxies from the SLUGS (Dunne et al. 2000), superposed with vertical dashed lines showing the upper limit on dust mass for the LBGs obtained in this paper. The three lines correspond, from left to right, to different cosmologies: ($\Omega_0 = 1$, $\Lambda = 0$), ($\Omega_0 = 0.2$, $\Lambda = 0.8$), and ($\Omega_0 = 0$, $\Lambda = 0$).

5. THE CROSS-CORRELATION FUNCTION BETWEEN SCUBA SOURCES AND LYMAN BREAK GALAXIES

We measured the SCUBA-LBG angular cross-correlation function in each field with a separate analysis for each sample in the 14 hr field. Figure 3 shows the positions of the LBGs and SCUBA sources for all three LBG samples. First, we calculated the angular separations of all the $N_s \times N_l$ SCUBA-LBG pairs in each field and then divided these into bins of angular distance. This procedure gives the basic function from the data, $N_{sl}(\theta_i)$ or LS .

We then generated a list of random galaxy positions for both the SCUBA sources and LBGs taking account of sensitivity variations in the images. Since we have two different sets of sources—SCUBA sources and LBGs—it is necessary to take account of the selection effects for both sets of sources. The Lyman break catalogs are subsets of larger catalogs drawn from a much larger area of sky than the SCUBA fields, and we generated lists of 5000 random positions for LBGs on the assumption that the sensitivity of all the catalogs is constant over the SCUBA fields.

The sensitivity of each SCUBA field is, however, very inhomogeneous (Eales et al. 2000; Webb et al. 2002). To generate lists of random positions for the SCUBA sources that take account of the variation in sensitivity of each SCUBA image, we adopted the following procedure.

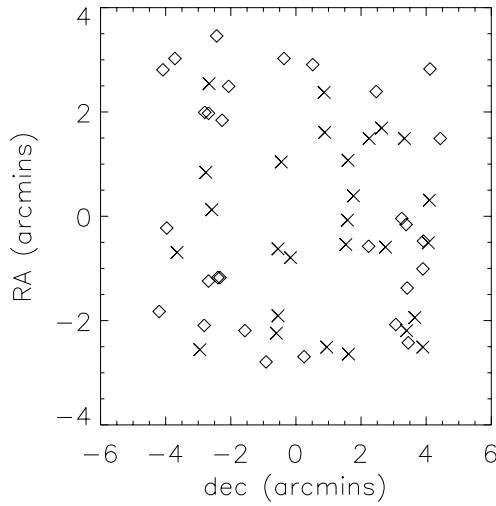


FIG. 3a

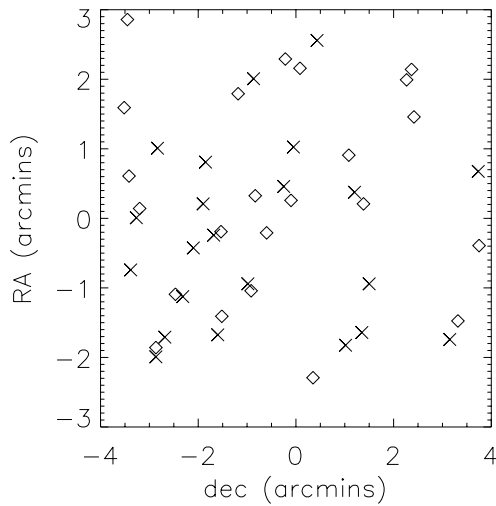


FIG. 3b

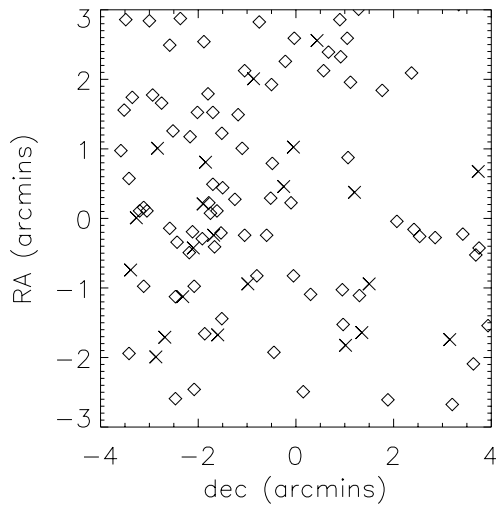


FIG. 3c

FIG. 3.—(a) Relative positions of the SCUBA sources and LBGs in the CUDSS 03 field. Diamonds correspond to LBGs and crosses to SCUBA sources. The sensitivity of the SCUBA map varies substantially over the entire field, while the LBGs are considered to be uniformly selected. (b) Same as (a), but for the CUDSS 14 field and the CFDF 14 field LBG sample. (c) Same as (a) and (b), but for the CUDSS 14 field and the Steidel 14 hr field LBG sample.

Using the best-fit submillimeter source counts from our survey (Eales et al. 2000; Webb et al. 2002), we produced lists of artificial random SCUBA sources. For each source, we produced a random position *on the assumption that there is no variation in sensitivity across the fields*. We then used the noise images for each field (Eales et al. 2000; Webb et al. 2002) to determine whether each artificial source would have been detected in our survey. In this way we produced a list of 5000 artificial SCUBA sources.

We calculated the angular separations of the real SCUBA sources and the N_{r_i} artificial LBGs, giving the function SR_L . We did likewise with the real LBGs and artificial SCUBA sources (LR_S), and finally the artificial SCUBA sources and artificial LBGs, giving the function R_LR_S . These functions must all be normalized to the same number of pairs as used to calculate LS .

We used two possible estimates of $w(\theta)$. The first of these is the Landy & Szalay 1993 formalism

$$w(\theta) = \frac{LS - (LR_S + SR_L) + R_LR_S}{R_LR_S}, \quad (2)$$

and the second is the Hamilton formula (Hamilton 1993)

$$w(\theta) = \frac{LS \times R_LR_S}{LR_S \times SR_L} - 1. \quad (3)$$

Both functions gave comparable results.

The final complication is that of the “integral constraint.” If $w(\theta)$ is estimated from an image, the integral

$$\frac{1}{\Omega^2} \iint w_{\text{est}}(\theta) d\Omega_1 d\Omega_2 \quad (4)$$

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 function is given by

$$w(\theta) = A(\theta^{-0.8} - C). \quad (5)$$

C can then be calculated from

$$C = \frac{\sum \theta_{ij}^{-0.8}}{N_{r_i} N_{r_s}}, \quad (6)$$

in which θ_{ij} is the angular distance between the i th artificial LBG and the j th artificial SCUBA source. For the 14 hr field this was calculated to be 0.0174, and for the 3 hr field, 0.0158.

Figure 4 shows our estimates of $w(\theta)$ for both fields. To estimate our errors we used the bootstrap method as outlined by Barrow, Bhavsar, & Sonoda (1984). We then fitted equation (5) using these values of C with the $w(\theta)$ results from each field and determined a cross-clustering amplitude of $5.2 \pm 2.9 \text{ arcsec}^{0.8}$ for the Steidel 14 hr sample, $1.1 \pm 4.4 \text{ arcsec}^{0.8}$ for CFDF 14, and $2.3 \pm 3.8 \text{ arcsec}^{0.8}$ for CFDF 03, where the errors are simply errors in the χ^2 fit. At separations of $10''$ these amplitudes correspond to $\omega(\theta) = 0.82 \pm 0.46$ for the Steidel et al. sample, $\omega(\theta) = 0.17 \pm 0.70$ for CFDF 14, and $\omega(\theta) = 0.36 \pm 0.60$ for CFDF 03. Clearly, the result from the Steidel et al. sample in the 14 hr field, which is the largest sample of the three, is the most (only) significant result and is quite large.

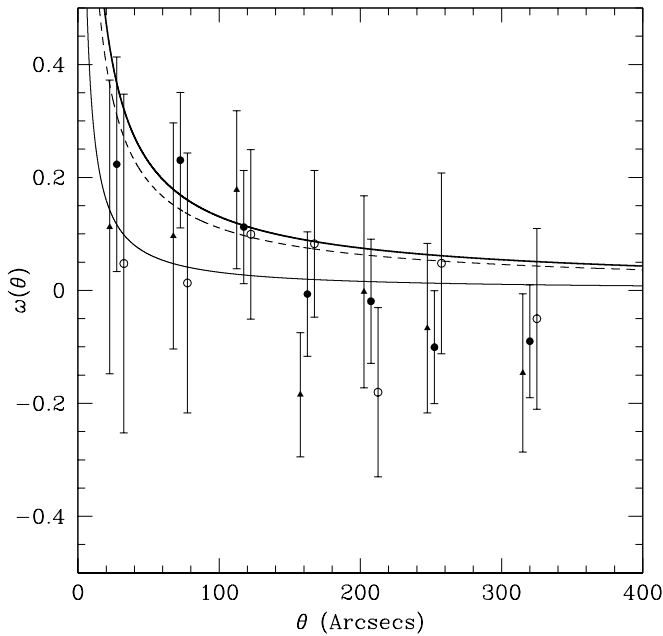


FIG. 4.—Angular cross-correlation function (SCUBA-LBG) for the three Lyman break samples. The triangles are for the 3 hr field, the filled circles are for the Steidel 14 hr field, and the open circles are for the CFDF sample of the 14 hr field. The upper, bold solid line is the LBG-SCUBA cross-correlation function measured in this paper (not including the integral constraint) for the Steidel et al. sample. This fit used only the inner four points, since beyond about $150''$ edge effects become important. The middle dotted line corresponds to the autocorrelation function of the bright ($S_{850\ \mu\text{m}} > 3\ \text{mJy}$) SCUBA sources from Webb et al. (2002). The lower solid line is the autocorrelation function for the LBGs from Giavalisco & Dickinson (2001).

In order to investigate the possibility that the 14 hr field is an unusually clustered region, we calculated the autocorrelation function of the Steidel et al. LBGs. The result is consistent with the results found in Giavalisco et al. (1998) using many fields over a larger area. For the brighter CFDF sample, S. Foucaud et al. (2003, in preparation) calculated an amplitude of $4.0 \pm 0.7\ \text{arcsec}^{0.8}$ for CFDF 14, which is slightly lower than the average of the three CFDF fields (CFDF 14, CFDF 03, and CFDF 22) of $4.7 \pm 1.2\ \text{arcsec}^{0.8}$. Therefore, the 14 hr field does not appear to be exceptional. The amplitude of the SCUBA-LBG cross-correlation function for CFDF 03 is comparable to the amplitude of the autocorrelation function of the brighter LBGs in the CFDF sample.

This analysis was performed assuming that the LBGs and SCUBA sources were not the same object, and so those objects within $8''$ of each other were included in the correlation signal. To be certain that these few objects were not biasing the clustering signal we redid the analysis, with the added restriction of $\theta > 8''$. We find the following amplitudes: for the Steidel et al. sample, $6.7 \pm 1.9\ \text{arcsec}^{0.8}$, for CFDF 14, $0.4 \pm 3.4\ \text{arcsec}^{0.8}$, and for CFDF 03, $3.8 \pm 3.9\ \text{arcsec}^{0.8}$. Therefore, it does not appear that the possible LBG-SCUBA associations are strongly affecting the correlation results.

In this analysis we have used the complete CUDSS SCUBA catalog of 50 sources. As this sample includes all sources detected above $3\ \sigma$, one might worry that a large number of spurious sources are contaminating the clustering analysis. However, in Eales et al. (2000) and Webb et al.

(2002) we discuss the number of expected spurious sources in the sample, using Gaussian statistical arguments and arguments based on an analysis of the noise in the SCUBA maps. We have concluded that about 2–3 sources in each field are spurious, or a total of 4–6 sources in the combined sample (or approximately 10%). At this level these sources are not expected to significantly alter the cross-clustering analysis.

However, to check this, we have repeated the clustering measurement using a subset of the 26 SCUBA sources in our catalog that were detected at $\geq 3.5\ \sigma$. For a larger sample size, one might expect the clustering amplitude to increase with the removal of the spurious sources in the sample; however, in doing so we are substantially decreasing our sample size (as we must remove all sources less than $3.5\ \sigma$, not just the 10% that are spurious). We measure the following clustering amplitudes: $A = 2.7 \pm 5.2\ \text{arcsec}^{0.8}$ for the 3 hr field, $A = 1.2 \pm 5.4\ \text{arcsec}^{0.8}$ for the 14 hr field, and CFDF 14, and $A = 5.1 \pm 5.5\ \text{arcsec}^{0.8}$ for the 14 hr field and the Steidel et al. sample, where the errors have again been estimated using the bootstrap method. The measured values are essentially the same as the amplitudes measured for the entire $\geq 3.0\ \sigma$ sample; however, the uncertainties have increased substantially because of the decrease in sample size. Hence, it does not appear that the analysis has been contaminated by spurious sources.

6. DISCUSSION

6.1. Submillimeter Flux of Lyman Break Galaxies

We detect, at a level of $\sim 2\ \sigma$, a mean submillimeter flux from the two CFDF samples of LBGs, but we do not detect any flux from the Steidel et al. sample. Recalling that the CFDF 14 LBGs are an optically bright subset of the Steidel LBGs, this could be taken as evidence of a positive correlation between observed optical and submillimeter flux. However, a plot of I -band magnitude versus recovered submillimeter flux shows no such correlation (Fig. 5). Similarly, no correlation is present when \mathcal{R} -band magnitude for the Steidel et al. sample is plotted versus submillimeter flux. In addition, there is no statistical detection of the submillimeter flux of a brighter subsample ($\mathcal{R} < 25$) of the Steidel et al. list (which agrees with the CFDF 14 catalog at approximately the 70% level).

On closer inspection, we find that the CFDF 14 measurement is completely dominated by the detection of one LBG, and when this object is removed from the list, a positive mean flux is detected only at the $1\ \sigma$ level. Although there are three detections of LBGs at greater than $3\ \sigma$ in the Steidel et al. list, they do not lift the mean flux of the entire 86 galaxy sample to a significant level. In CUDSS 03, where no LBG was detected above $3\ \sigma$, the positive detection of flux is not due to any single object.

It is not entirely surprising that we see no correlation between the submillimeter and observed optical flux. Many authors (Shapley et al. 2001; Adelberger & Steidel 2000) have claimed that galaxies with higher intrinsic UV luminosities (after correcting for reddening) contain larger dust masses. However, this does not necessarily translate into a correlation between *observed* optical and submillimeter flux. Indeed, as with our results, Shapley et al. (2001) found no correlation between dust content and observed optical flux.

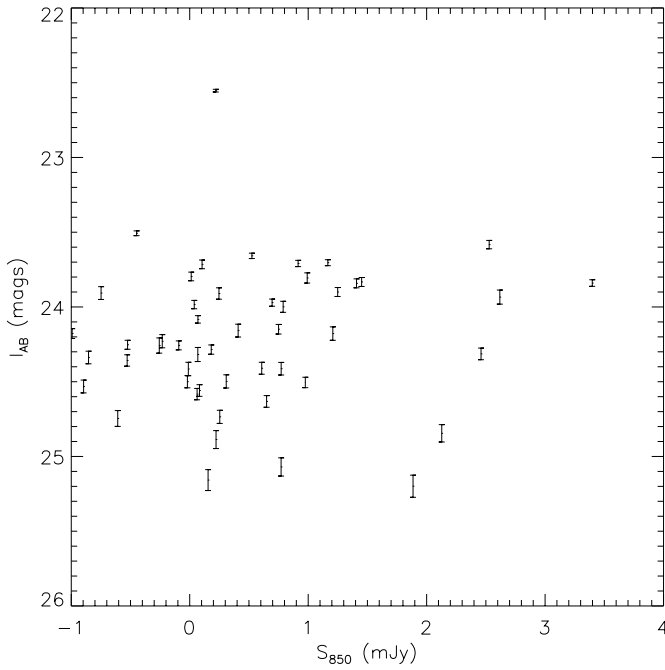


FIG. 5a

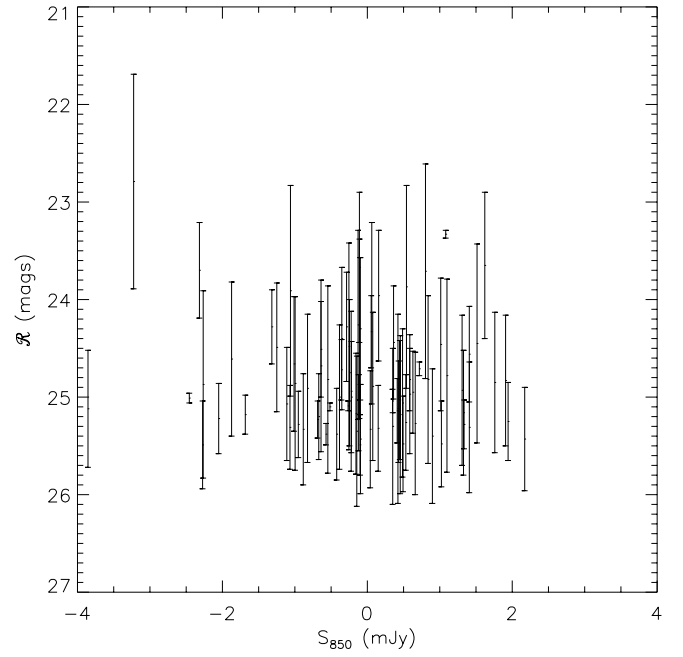


FIG. 5b

FIG. 5.—(a) *I*-band flux of the CFDF LBGs for both the 3 and 14 hr fields vs. their recovered 850 μm flux. (b) *R*-band flux of the Steidel 14 hr field LBGs vs. their recovered 850 μm flux.

Two other groups have attempted to directly measure the submillimeter flux of high-redshift star-forming galaxies. Chapman et al. (2000) carried out a targeted study of eight LBGs, selected to have high UV-derived SFRs, and they obtain a result similar to our own. Although one object was detected at greater than 3σ , no flux was detected statistically from the sample as a whole once this object was excluded. However, in a recent conference proceeding (Chapman et al. 2001a), with a larger sample of 33 red and high star-forming LBGs, they report a statistical detection of $S_{850} = 0.6 \pm 0.2$ mJy with marginal detections for several individual red LBGs.

Peacock et al. (2000) followed a similar approach to this paper for starburst galaxies in the HDF and detected a mean flux of 0.2 ± 0.04 mJy (for an SFR of $1 h^{-2} M_{\odot} \text{yr}^{-1}$) with the mean flux increasing with SFR. To directly compare this result with our own we must first convert our statistical measurement to units of submillimeter flux per unit SFR. To determine the UV-estimated SFRs for the LBGs in our three samples we follow the method outlined in Peacock et al. (2000) and Madau et al. (1996). Approximately 60% of the Steidel et al. LBGs in our field have spectroscopic redshifts. For those without spectroscopic redshifts, and for the CFDF LBGs, we assumed a redshift of $z = 3$. We chose a flat $\Omega_{\Lambda} = 0.7$ cosmology. We find

$$\frac{S_{850\mu\text{m}}}{\text{mJy}} = 0.015 \pm 0.022 \frac{\text{SFR}}{h^{-2} M_{\odot} \text{yr}^{-1}} \quad (\text{Steidel et al. 14 hr sample}), \quad (7)$$

$$\frac{S_{850\mu\text{m}}}{\text{mJy}} = 0.065 \pm 0.034 \frac{\text{SFR}}{h^{-2} M_{\odot} \text{yr}^{-1}} \quad (\text{CFDF 14 hr sample}), \quad (8)$$

$$\frac{S_{850\mu\text{m}}}{\text{mJy}} = 0.13 \pm 0.06 \frac{\text{SFR}}{h^{-2} M_{\odot} \text{yr}^{-1}} \quad (\text{CFDF 03 hr sample}). \quad (9)$$

Of our three LBG samples only the statistical measurement from CFDF 03 is consistent with the results of Peacock et al. (2000). The Steidel et al. sample and the CFDF 14 sample both have much lower detections. Peacock et al. (2000) converted the results of Chapman et al. (2000) to these units and found

$$\frac{S_{850\mu\text{m}}}{\text{mJy}} = 0.13 \pm 0.14 \frac{\text{SFR}}{h^{-2} M_{\odot} \text{yr}^{-1}}, \quad (10)$$

which is consistent with the Peacock et al. (2000) result, although also consistent with no detection of submillimeter flux. It appears that most LBGs are not strong submillimeter emitters, that is, with $0.3 < S_{850\mu\text{m}} < 3$ mJy, and therefore the strength of a statistical submillimeter detection may depend strongly on the properties of the specific LBG sample observed.

In Figure 6 we plot the mean 850 μm flux as a function of UV-estimated SFR for all three LBG samples. Although, to the eye, somewhat suggestive of a rise, these data are consistent with no correlation between the SFR and the submillimeter flux.

As discussed in § 4 there are four LBGs that are possibly identified with a SCUBA source at greater than 3σ , one from the CFDF 14 sample and three from the Steidel et al. sample. There are very few Lyman break or high-redshift star-forming galaxies (from all studies) that are known to be submillimeter bright, and therefore conclusions regarding any unifying properties are difficult. There is some suggestion, however, that these objects have extremely red colors

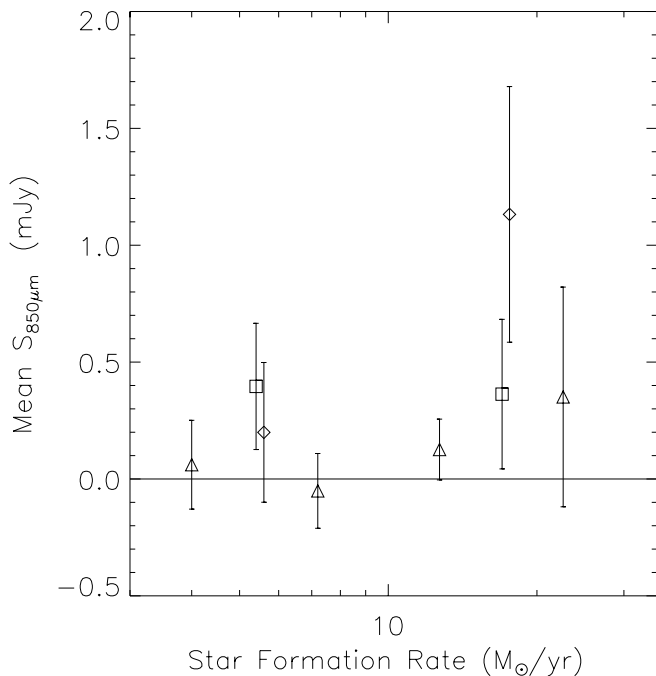


FIG. 6.—Mean 850 μm flux as a function of UV-estimated SFR. The squares and diamonds correspond to the CFDF 14 and CFDF 03 samples, respectively. The triangles represent the Steidel 14 hr list. Because of our small sample size we are restricted to only two bins for the CFDF fields and four for the Steidel field. The points are consistent with no detected rise in flux with SFR.

compared to the average for the population (Chapman et al. 2000, 2001a). As discussed in Shapley et al. (2001), the more intrinsically luminous LBGs appear to be dustier, with redder optical colors, and should therefore be brighter in the submillimeter. However, we see no such trend with the four LBGs identified with bright SCUBA objects in our sample, although we have very limited photometric information, particularly in the near-infrared, on these faint objects.

We estimate that the LBGs from the two CFDF samples could be producing, at most, 20% of the background at 850 μm , when integrated over all redshifts. The Steidel LBGs, which are a deeper sample, have an upper limit to their contribution of 19%. However, as outlined in Chapman et al. (2000), the LBGs that are most likely to dominate the submillimeter background, the highly reddened galaxies, are less likely to be detected in these optical LBG surveys, and therefore our sample may be biased to submillimeter faint objects.

6.2. The SCUBA-LBG Cross-Correlation Function

The angular cross-correlation functions between the SCUBA sources and the three LBG samples are presented in Figure 4. There are some interesting results from this clustering analysis. The first is that, although we measure consistent clustering amplitudes for all three samples, our strongest LBG-SCUBA cross-clustering signal is detected in the Steidel et al. sample in the 14 hr field. Recent results from Giavalisco & Dickinson (2001) and S. Foucaud et al. (2003, in preparation) have shown clustering segregation with UV luminosity for the autocorrelation function of the LBGs, such that the brighter objects are more strongly clustered. Thus, one might posit that we should see a stronger

clustering signal in the CFDF samples. Unfortunately, the smaller numbers in the brighter CFDF samples mean that even if a stronger signal were present, it would be harder to detect.

A second result is that the measured amplitude of the cross-clustering between the 14 hr SCUBA sources and the Steidel LBGs is larger than for the autoclustering of the LBGs themselves, although certainly consistent within the error. The strength of the LBG-SCUBA angular cross-clustering is essentially a lower limit on the true spatial clustering as it is projected over a broad redshift range. The actual spatial cross-clustering is expected to be even higher, since the range in the redshift distribution of the SCUBA sources is much broader than that of the LBGs. As a further check we repeated the cross-correlation analysis after removing SCUBA sources with secure identifications with $z < 2$ (Eales et al. 2000; T. M. Webb et al. 2003, in preparation; D. L. Clements et al. 2003, in preparation) and found the correlation signal increased as would be expected for real clustering.

By assuming a redshift distribution for the SCUBA sources (including those with $z < 2$) we can estimate r_0 for the spatial LBG-SCUBA cross-correlation function following the procedure in, for example, Efstathiou et al. (1991). Although the redshift distribution is still highly uncertain, the results of many groups are not inconsistent with a median redshift near $z = 3$ and with only a small fraction of objects below $z = 2$ (see the review by Dunlop 2001 and references therein). We therefore take our general redshift distribution to be a Gaussian centered at $z = 3$ with $\sigma = 0.8$. We adopt the redshift distribution of Giavalisco et al. (1998) for the Steidel LBGs and $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ cosmology. Given these parameters we find $r_0 = 11.5 \pm 3.0 \pm 3.0 h^{-1}$ Mpc for the Steidel et al. sample. The first error is simply the statistical error calculated from $\omega(\theta)$ and $\delta\omega(\theta)$. The second error is systematic and is estimated by varying the redshift distribution of the SCUBA sources from $\bar{z} = 2.5$ to $\bar{z} = 3.5$, and Δz from 0.6 to 1.1. The redshift distribution of the CFDF LBG samples is slightly different than that of Steidel et al. We estimate the CFDF distribution as a Gaussian of the same standard deviation (0.24) but centered at $z = 3.2$. For the CFDF 14 amplitude of $1.1 \pm 4.4 \text{ arcsec}^{0.8}$ we find $r_0 = 4.5 \pm 7.0 \pm 5.0 h^{-1}$ Mpc, and for CFDF 03 (with an amplitude of $2.3 \pm 3.8 \text{ arcsec}^{0.8}$) we find $r_0 = 7.5 \pm 7.0 \pm 5.0 h^{-1}$ Mpc.

The two values of r_0 determined from the SCUBA-CFDF results are comparable (within their large uncertainties) to those measured for the LBG autocorrelation function in the two fields. In the CFDF survey, for $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ cosmology, S. Foucaud et al. (2003, in preparation) estimated $r_0 = 6.4 \pm 0.3 h^{-1}$ Mpc for the 3 hr field and $r_0 = 5.1 \pm 0.5 h^{-1}$ Mpc for the 14 hr field.

We consider the Steidel LBG-SCUBA cross-correlation result to be the most secure. For Steidel LBGs with $\mathcal{R} < 25.5$, Giavalisco & Dickinson (2001) found $r_0 = 3.2 \pm 0.7$ for the autocorrelation function, for the same cosmology that is smaller than our result for this field, although within the uncertainty range. One simple argument suggests that a higher value for the amplitude of the LBG-SCUBA cross-correlation function than for the LBGs themselves would not be unexpected. The high value of the autocorrelation function for LBGs alone has been explained by the large values of bias expected for rare systems in the early universe (Kaiser 1984; Giavalisco et al. 1998). Indeed,

the more luminous LBGs have been shown to be more highly clustered (Giavalisco & Dickinson 2001). Luminous SCUBA sources are much rarer objects than LBGs, and so the bias values may be even higher. This argument breaks down if SCUBA sources are the result of rare or short-lived stochastic processes in the universe, in which case they need not be highly clustered at all, with themselves, or with the LBGs.

Webb et al. (2002) and Scott et al. (2002) have measured the autoclustering strength of SCUBA sources. Although hampered by small areas and numbers, the results are consistent with strong autoclustering, at least as strong as the autoclustering of LBGs and extremely red objects. Webb et al. (2002) find an angular correlation amplitude of $4.4 \pm 2.9 \theta^{-0.8}$. Assuming the same redshift distribution as above, this may be inverted to a spatial amplitude of $12.8 \pm 7.0 h^{-1}$ Mpc.

It is tempting to draw an analogy with the universe at low redshift, where the amplitude of the correlation function for rare clusters of galaxies is ~ 18 times higher than that for galaxies themselves, with the amplitude of the cross-correlation function between clusters and galaxies being midway between these values (Bahcall 1988). Circumstantial evidence in favour of this idea is the discovery of clusters of submillimeter sources around the extremely rare high-redshift radio galaxies (Ivison et al. 2000), suggesting again that SCUBA sources preferentially form in much rarer environments than the more common LBGs. However, from the results of this work we may only say that the cross-clustering between the SCUBA sources and LBGs is at least consistent with the strengths of the self-clustering in the individual populations.

A cross-clustering signal has also been detected between very bright SCUBA objects and *Chandra* sources (Almaini et al. 2001), with an even larger amplitude than that found in this work. X-ray-bright objects, as with submillimeter-bright objects, are relatively rare and, therefore, following the same logic as above should also be very highly clustered.

The possible angular cross-clustering signal measured in the Steidel 14 hr field is suggestive evidence that many of the SCUBA sources in this field are indeed at the same high redshifts as the LBGs. The smaller angular cross-clustering signal in the 3 hr field may indicate that the SCUBA sources in this field do not lie at the same redshifts as the LBGs and would suggest a difference in the redshift distribution of SCUBA sources in the 3 and 14 hr fields (see Fig. 6).

The positive clustering signal should be remembered when attempting to determine identifications for SCUBA sources by positional coincidence or when observing individual LBGs with a large-beam telescope such as the JCMT. Positive submillimeter flux could erroneously be associated with a nearby LBG rather than the object actually producing the emission, which might be undetected at optical

wavelengths. Indeed, this may be the case with our own LBG identifications and those of other authors, in particular, submillimeter-bright LBGs that do not show unusual colors or luminosities.

7. CONCLUSIONS

We have used the 850 μm maps from the Canada-UK Deep Submillimeter Survey to study (1) the submillimeter flux and dust properties of Lyman break galaxies and (2) the angular correlation between Lyman break galaxies and SCUBA sources. We obtain the following results:

1. We marginally detect (at the 2σ level) submillimeter flux from LBGs in the CFDF 14 and CFDF 03 samples, but we do not detect flux from the Steidel et al. sample. The flux levels are 0.382 ± 0.206 mJy for the 14 hr field and 0.414 ± 0.263 mJy for the 3 hr field. Furthermore, we show that possibly because of LBG-SCUBA clustering, SCUBA sources not identified with an LBG galaxy must be removed from the map before a proper analysis can be performed.

2. LBGs are the best optical identification for four SCUBA sources; however, it is possible that some of these identifications may be incorrect. There are indications that these objects may lie in a region of spatial overdensity.

3. An upper limit for the dust mass of LBGs was calculated from their submillimeter flux results and we conclude that these masses can be no larger than those of nearby galaxies.

4. The SCUBA-LBG correlation function was measured for all three sample of LBGs. We found a high amplitude $r_0 = 11.5 \pm 3.0 \pm 3.0 h^{-1}$ Mpc for the Steidel et al. sample, $r_0 = 4.5 \pm 7.0 \pm 5.0 h^{-1}$ Mpc for CFDF 14, and $r_0 = 7.5 \pm 7.0 \pm 5.0 h^{-1}$ Mpc for CFDF 03 (where the first error is statistical and the second systematic).

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