AN 850 MICRON SCUBA SURVEY OF THE HUBBLE DEEP FIELD–NORTH GOODS REGION

W.-H. WANG,1 L. L. COWIE,1 AND A. J. BARGER1,2,3

Received 2004 February 24; accepted 2004 June 9

ABSTRACT

The Hubble Deep Field–North (HDF-N) is one of the best-studied extragalactic fields, and ultradeep optical, radio, X-ray, and mid-infrared wide-field images are available for this area. Here we present an 850 μm survey around the HDF-N, covering most of the area imaged by the Advanced Camera for Surveys as a part of the Great Observatories Origins Deep Survey. Our map has 0.4–4 mJy sensitivities (1σ) over an area of ~110 arcmin², and there are 45 sources detected at greater than 3σ. After correcting for the effects of noise, confusion, incompleteness, and the Eddington bias using Monte Carlo simulations, we find that the detected 850 μm sources with fluxes greater than 2 mJy have a surface density of 3200+1900−1000 deg⁻² and account for about 24%–34% of the far-infrared extragalactic background light. Using the deep radio interferometric image and the deep X-ray image, we are able to accurately locate ~60% of the bright submillimeter sources. In addition, by assuming the Arp 220 spectral energy distribution in the submillimeter and radio, we estimate millimetric redshifts for the radio-detected submillimeter sources and redshift lower limits for the ones not detected in the radio. Using the millimetric redshifts of the radio-identified sources and spectroscopic and optical photometric redshifts for galaxies around the submillimeter positions, we find a median redshift of 2.0 for 11 possibly identified sources, or a lower limit of 2.4 for the median redshift of our 4σ sample.

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

1. INTRODUCTION

Recent deep submillimeter surveys with the Submillimeter Common-User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT) and the Max Planck Millimeter Bolometer array on the IRAM telescope have resolved the far-infrared (FIR) extragalactic background light (EBL) detected by COBE (e.g., Puget et al. 1996; Fixsen et al. 1998; Hauser et al. 1998) at 850 μm and 1.2 mm into discrete sources (Smail et al. 1997; Barger et al. 1998, 1999a; Hughes et al. 1998; Eales et al. 1999, 2003; Bertoldi et al. 2000; Chapman et al. 2002; Cowie et al. 2002; Scott et al. 2002; Webb et al. 2003b). In blank-field surveys, the resolved point sources with 850 μm fluxes in the 2–10 mJy range account for 20%–30% of the FIR EBL. The 2–10 mJy flux range corresponds to ~10¹²–10¹³ L₀ FIR luminosity at redshifts greater than 1, where the observed submillimeter flux is not a function of redshift because of the steep dust spectrum in the submillimeter (see, e.g., Blain & Longair 1993). Thus, the bright submillimeter source population is inferred to be the distant analog of the local ultraluminous infrared galaxy population (Sanders & Mirabel 1996). In lensing cluster field surveys, a further 45%–65% of the FIR EBL is resolved into point sources with 0.3–2 mJy intrinsic 850 μm fluxes, corresponding to more “normal” 10¹¹ L₀ galaxies (Cowie et al. 2002).

Observations suggest that these submillimeter sources, which dominate the FIR EBL, are mainly high-redshift (z > 1) starburst galaxies (Barger et al. 1999b, 2000; Fox et al. 2002; Chapman et al. 2003a) whose submillimeter emission mostly comes from dust heated by young, massive stars. Because the observed FIR EBL is comparable to the total optical/UV EBL, these submillimeter sources are crucial to understanding the integrated star formation history of the universe and may be the dominant component of star formation at z > 1 (e.g., Barger et al. 2000; Gispert et al. 2000; Chapman et al. 2003a).

In order to better understand the evolution of the submillimeter sources and the star formation history, it is crucial to accurately determine the surface density of the submillimeter sources, to determine their properties at other wavelengths, and to measure their redshifts. The surface density of submillimeter sources brighter than 2 mJy was previously determined to be only ~0.5 arcmin⁻² (e.g., Barger et al. 1999a; Eales et al. 2000), implying that any statistical study of this population requires a large survey area. It is much more difficult, however, to measure the redshift distribution of the submillimeter sources. The fundamental reason is that the current submillimeter telescopes have very low resolution, as compared to optical telescopes. In most cases, a few optical galaxies are found within a submillimeter telescope beam, and it is difficult to unambiguously identify the real counterparts to the submillimeter emission. It is also time-consuming to measure the redshifts for each of these counterpart candidates (Barger et al. 1999b). Radio interferometric imaging is the method most commonly used to solve this problem. By assuming that the correlation between the FIR and radio fluxes of normal galaxies (i.e., galaxies without active galactic nuclei) in the local universe (see, e.g., Condon 1992) also holds for the submillimeter sources, radio sources near the submillimeter positions can be identified as counterparts (Barger et al. 2000) and the redshifts of the associated optical galaxies may be measured (Chapman et al. 2003a). In addition, redshifts of the submillimeter sources could also be independently estimated using the radio and submillimeter fluxes by assuming a plausible spectral energy distribution (SED; Carilli & Yun 1999; Barger et al. 2000; Yun & Carilli 2002). The
limitation of the radio identifications is that only \( \approx 60\% \) of the bright \((>6\text{ mJy})\) submillimeter sources have radio counterparts (Barger et al. 2000; Ivison et al. 2002; Chapman et al. 2003b). Accurate positions and redshifts for most of the submillimeter sources still cannot be measured and will have to await the advent of high-resolution submillimeter observations, which are now becoming possible with the advent of the Submillimeter Array (Moran 1998).

We have been carrying out an 850 \( \mu \text{m} \) SCUBA survey of intermediate depth (0.4–4 \( \text{mJy} \ 1\sigma \) sensitivity) over a large area \((\approx 110 \text{ arcmin}^2)\) centered on the Hubble Deep Field–North (HDF-N). Early results of this survey targeting optically faint radio sources were published in Barger et al. (2000). Our 850 \( \mu \text{m} \) survey covers most of the area imaged by Great Observatories Origins Deep Survey (GOODS), using the Advanced Camera for Surveys (ACS) on the Hubble Space Telescope \((HST)\); Giavalisco et al. 2004) and a large part of the Chandra Deep Field–North (CDF-N) observed by Chandra (Alexander et al. 2003). This field also has deep radio and mid-infrared (MIR) imaging (Richards 2000; Aussel et al. 1999), as well as ultradeep ground-based optical and near-infrared (NIR) imaging (Capak et al. 2004). The deep radio image at 1.4 GHz provides accurate astrometry and milli-arcsecond redshift estimates for the submillimeter sources that have radio counterparts. Our goal is to better constrain the number counts of bright submillimeter sources and to use the deep multiwavelength data to understand the redshift distribution and properties of the submillimeter sources. In this paper, we present the 850 \( \mu \text{m} \) source catalog, number counts, and optical, radio, X-ray, and MIR counterpart candidates to the submillimeter sources.

2. OBSERVATIONS AND DATA REDUCTION

SCUBA jiggle maps at 850 \( \mu \text{m} \) of the HDF-N flanking fields were obtained in multiple runs between 1999 and 2003 under excellent submillimeter weather conditions \((\tau_{225} < 0.08)\). The maps obtained in April and June of 1999 were published in Barger et al. (2000). Each of the SCUBA maps covers an \( \approx 2\text{\,arcmin}^2 \) field of view and has typical integration times between 10 and 30 ks, depending on weather conditions and other observational constraints. The maps were dithered with \( 10\text{°} – 20\text{°} \) offsets. The dithering and the instrumental rotation on the sky prevent most regions of the sky from continuously falling on bad bolometers. Chopping of the secondary was fixed in the R.A. direction with a 45\( ^\circ \) chop throw. Such a chop produces two 50\% negative sidelobes to the east and west of the primary beam, which has a 145\( \text{\,FWHM} \). The 45\( ^\circ \) chop throw was chosen so that each detected source would have at least one sidelobe inside the 2.3 field of view. This effectively increases the on-source integration time.

Pointing checks were performed before and after each \( \approx 1 \text{ hr} \) of on-source observation and every time after transit. A nearby radio source \((0954+685, 1418+546, 0923+392, 1308+326, \text{or} 1044+719)\) was used for the pointing checks. The typical pointing offset is \( \leq 1\text{\,arcsec} \), and no offset greater than 2\( \text{\,arcsec} \) was observed. The JCMT has noted a newly discovered tracking error.\(^4\) We calculated the pointing error caused by this and found that most of our target fields and pointing sources have combined tracking errors of \( \leq 1\text{\,arcmin} \), comparable to the normal pointing errors. A few observations at coordinates 12\( ^h \)37\( ^m \), +62°13´ (J2000.0) have 18 errors, corresponding to 0.12 times the beam FWHM. These observations contribute 25\% to the integration time in this region. We thus conclude that our pointing and astrometry are not seriously affected by this tracking error.

Flux calibration was performed every night using the primary calibrator Mars or the secondary calibrators CRL 618, CRL 2688, IRC +10216, or OH 231.8. If the variable calibrator IRC +10216 was used, a nonvariable calibrator, such as CRL 618 or a primary calibrator, would be observed in the same run to confirm its light curve. On each night, the flux was calibrated using a 30\( ^\circ \) aperture centered at the primary beam of the calibrator. The size of the aperture is not critical in this research as long as the same aperture size is adopted each night. This is because the filter function we used for flux measurements will be renormalized by a calibrator \((\text{see} \S\ 3)\), and the flux measurement is independent of the aperture size. The sky opacity was monitored during the observations in various ways. Standard “sky dips” that give the most reliable 850 \( \mu \text{m} \) opacities were obtained every 2–4 hr, depending on the stability of the weather. The JCMT water vapor monitor \((WVM)\) was used when available to obtain the sky opacity every 6 s toward the same direction as the telescope beam. When the WVM was not available, opacity values from the Caltech Submillimeter Observatory Tau-Dipper \((\tau_{\text{CSO}})\) were used to monitor the opacity change every 10 minutes. We found that for most of the time, the sky-dip values were consistent with the WVM values, while the \( \tau_{\text{CSO}} \) values have larger errors.

The jiggle maps described above contain 73.2 hr of integration in total. In addition to our maps, we also used that part of the ultradeep jiggle map centered at the HDF proper from the archive that had matched chopping. This ultradeep map was first presented in Hughes et al. (1998) and was extensively analyzed by Serjeant et al. (2003). We did not attempt to fully reproduce their results, and we did not use all of the archival data. We only included the data taken with a 45\( ^\circ \) east-west chop throw, identical to our standard one. In other words, our final jiggle map contains all the SCUBA data taken with an identical strategy. This gives a uniform point-spread function \((PSF)\) over the entire field and allows us to analyze the data in a consistent way \((cf.\ the\ HDF\ supermap\ that\ contains\ a\ scan\ map\ and\ jiggle\ maps\ taken\ with\ various\ chops;\ Borys\ et\ al.\ 2003)\). The data included here consist of 94.7 hr of integration and cover an area of \( \approx 110 \text{ arcmin}^2 \) with 0.4–4 \( \text{mJy} \) \((1\sigma)\) point-source sensitivity.

The data were reduced using the SCUBA User Reduction Facility package \((SURF;\ Jennes\ \&\ Lightfoot\ 2000)\). In SURF, the data were flat-fielded, atmospheric extinction–corrected, and pointing-corrected, and the sky noise was removed in standard ways.\(^5\) The extinction correction made use of the sky-dip results, when the opacity was stable, or the WVM

\(^4\) See http://www.jach.hawaii.edu/jacpublic/jcmt/facility_description/pointing/tracking_fault.html.

\(^5\) Borys et al. (2003) mentions that in our spring 2003 data there is a periodic noise artifact with a time scale that is the same as the 16 point jiggle pattern. We noticed this noise in our data taken in 2003 March during our data reduction. About \( \frac{1}{3} \) of the bolometers suffered from this periodic noise \((C.\ Borys\ 2003,\ \text{private communication})\), but only a few bolometers \((\approx 5)\) showed strong noise signals. We inspected all of the data and manually removed the bolometers showing such strong noise signals. Other bolometers potentially having this problem were excluded during the sky noise removal but were still included in our final maps. Because we already took the bolometer variance \((\text{represented by the weight assigned to each bolometer})\) into account when making maps and extracting sources, these noisy bolometers should not affect our analyses.
results, when the opacity varied rapidly. Before maps were made, the data were weighted according to the bolometer variance relative to the central bolometer in the first observation. Maps were made in SURF with the rebin routine. However, because rebin cannot handle more than 200 observations (we had 244 observations), we divided the data into two roughly equal halves and rebinned them individually. The rebin routine generated the sky, integration time, and weight maps from each half of the data. We then combined the two sets of maps to form the final sky, integration time, and weight maps. We present our final sky map in Figure 1.

In addition to the sky map, we also constructed a “true-noise” map in which all of the sources have been cleaned out, such that the map contains only the bolometer and sky noise, following the procedure introduced in Cowie et al. (2002). After bright sources were detected and removed from each of the two half-maps using the method described in § 3, the true-noise map was constructed by subtracting the two half-maps from each other. The map was then scaled by the factor \((t_1t_2)^{1/2}/(t_1 + t_2)\), where \(t_1\) and \(t_2\) are weighted integration times for each pixel in the two half-maps. This effectively removes all celestial objects. Noise measured in this way is generally lower than that directly measured from the sky map, which contains confusion noise from undetected faint sources. In particular, for the deepest region in the HDF proper, where confusion becomes important, we found that the true noise is \(\sim 10\%\) lower than that measured from the cleaned sky map. In this paper, all analyses are based on the true noise.

3. SOURCE IDENTIFICATION AND CATALOG

Our source detection algorithm is optimized for single, pointlike sources. To detect such sources, the optimal filter function is the telescope beam inversely weighted by the noise in each pixel. The telescope beam includes the primary beam and the two negative sidelobes. This allows recovery of the integration times on the sidelobes and enhances the signal-to-noise ratio (S/N) of the detected sources. Such S/N enhancement is up to \(\sim 20\%\) if both sidelobes fall in the field of view. The noise of each pixel is represented by the integration time and bolometer variance that is contained in the weights assigned to the pixel. We thus calculated the beam-optimized flux map \((F_0\), hereafter the flux map) using

\[
F_0 = \frac{STW \odot P}{TW \odot P^2},
\]

where \(S\) is the sky map, \(T\) is the integration time map, \(W\) is the weight map, \(P\) is the normalized beam response, and \(\odot\) denotes convolution. The telescope beam response was obtained from observations of pointlike calibrators. It was normalized to yield correct point-source fluxes by using equation (1) on a calibrator. The flux calculated with equation (1) also yields the minimum \(\chi^2\) for point sources (see Serjeant et al. 2003 for the derivation). The error associated with the beam-optimized flux (i.e., \(1 \sigma\) sensitivity) was calculated by propagating the errors in equation (1) using

\[
\sigma_F \propto \frac{1}{(TW \odot P^2)^{1/2}}.
\]

The proportionality is because SURF arbitrarily normalizes weight and integration time to the central pixel in the first observation. The proper normalization of equation (2) utilizes the true-noise map. The error map from equation (2) was scaled by a constant so that the noise flux measured using equation (1) in the true-noise map has a mean S/N of 1. The normalized error map is presented in Figure 2. An S/N map was made by dividing the flux map by the error map.

3.1. Direct Source Extraction

Source identification was performed in the S/N map. S/N peaks calculated from equations (1) and (2) are peaks of minimum \(\chi^2\). In principle, these peaks could be considered candidate detections and their fluxes and errors could be measured in the flux and error maps. However, especially for faint sources, the fluxes measured in this way may be altered by the sidelobes of nearby sources. There are several ways to
solve this problem. The simplest approach is to remove bright sources from the map before fluxes of fainter sources are measured. We note that the sources with high S/N are also the brighter ones locally. Therefore, we first measured the flux of the highest S/N peak and removed the corresponding PSF to 1.5 $\sigma$ from the sky map at the S/N peak location. The amount of flux removed and the location of the S/N peak were recorded. This location of the S/N peak is used as the source position in the final catalog. Then we recalculated the flux map and the S/N map from the residual sky map to identify and remove the next-highest S/N peak. We repeated this until the S/N was less than 3.0 everywhere. The depth of source removal was 1.5 $\sigma$; i.e., there was 1.5 $\sigma$ residual flux on the sky map after each source was removed. We observed that if values of $\leq 1.0$ $\sigma$ (the flux uncertainty) were used, errors would grow rapidly and some “new sources” would be created. Because not all of the fluxes were removed, we measured the fluxes of all identified sources in the final residual flux map and added these fluxes back to the cataloged fluxes. The procedure above reduces the interference of nearby sources to less than 0.8 $\sigma$, because the 1.5 $\sigma$ flux limit leaves a 0.8 $\sigma$ residual flux in the sidelobes. For sources that do not fall exactly on each other’s sidelobes, the residual interference would be even smaller and thus negligible.

The source catalog constructed in this way is presented in Table 1 and Figure 3. A total of 17 sources are detected at greater than 4 $\sigma$. Only sources detected above this significance level should be considered secure detections. At lower significance, many of the sources will be real, but some will correspond to noise peaks. There are a further 28 sources between 3 and 4 $\sigma$. In § 5.1, we estimate the number of spurious detections caused by noise to be $\sim 7–10$ in the 3.0–4.0 $\sigma$ range, and most of these are in the residual sources in the 3.0–3.5 $\sigma$ range. Of the 10 sources in the 3.5–4.0 $\sigma$ range, we expect $\sim 1$ to be a spurious source.

The procedure described above assumes isolated, pointlike sources. However, there might be extended sources or multiple blended sources that are marginally resolved. It is also possible that the PSF of a detected source is damaged by a noisy bolometer. For such sources, the PSFs are not pointlike. One example is GOODS 850-13. After it was removed from the map, another significant peak (GOODS 850-23) still existed in its neighborhood. Another example is source GOODS 850-6. This source happened to fall close to a bad bolometer during the observations. Its observed PSF is altered by that bolometer and shows two peaks (Fig. 1), although it is still consistent with a single source. Being aware of this, we also list fluxes measured within 30” diameter apertures in Table 1. Sources with aperture fluxes significantly greater than the beam-optimized fluxes (e.g., GOODS 850-5, 6, 13, and 16) may be marginally resolved by the telescope beam or affected by noisy bolometers. We caution that for such sources, the cataloged multiples should not be considered unique configurations of the flux distribution. The exact source shape and multiplicity can only be revealed by optical/NIR or radio identifications or by submillimeter interferometric imaging.

### 3.2. CLEAN Deconvolution

In addition to the direct source extraction described above, another method to solve the sidelobe interference is to deconvolve the map with the telescope beam, as most radio astronomers do. We performed standard CLEAN deconvolution on our map, also based on beam-optimized fluxes. In our CLEAN deconvolution, the highest S/N peak was identified and a small portion (10%–20%) of its flux was removed (CLEANed) from the sky map. The next flux map was then constructed from the residual sky map, the next-highest S/N peak was CLEANed, and so on. Each time some flux was CLEANed, the flux and the location were recorded in a catalog. The CLEANing was stopped after the S/N on the map was less than 1.5 everywhere. There is a difference between our version of CLEAN and the normal CLEAN used in most radio astronomy. Our CLEAN removes sources at the beam-optimized S/N peaks, while normal CLEAN removes sources at the peaks on the sky map. Given the low S/N of the SCUBA map (<5 for most sources) and the very nonuniform sensitivity, we believe that our method provides more reliable results.

It is apparent that the direct extraction method in § 3.1 is a simplified CLEAN—it removes the flux of a source at once, instead of just removing a small portion of the flux. Indeed, the catalog generated by the CLEAN deconvolution is in excellent agreement with Table 1, and there is no point in listing it separately. The only differences between the CLEAN catalog and Table 1 are in the marginally resolved sources. For these sources, the direct extraction provided a configuration that has the fewest pointlike components, while CLEAN generated many faint point sources within a comparable beam size. Again, we caution that for marginally resolved sources, both the direct extraction results and the CLEAN results are approximate models for the flux distribution. Neither of them provides a unique deconvolution solution.

### 4. COMPARISON WITH PREVIOUS 850 $\mu$m CATALOGS

The HDF and its flanking fields have been investigated at 850 $\mu$m with SCUBA by several other groups. In this section, we compare our source catalog with the ones in these surveys.

#### 4.1. HDF-Proper Jiggle Map

Hughes et al. (1998) and Serjeant et al. (2003) surveyed the HDF-proper area, using the jiggle mode of SCUBA. Their survey covered an area of $\sim 10$ arcmin$^2$, with $\sim 0.2–1.5$ mJy sensitivity. Our map of the HDF-proper region made use of a subset of the observations of Hughes et al. (1998) and Serjeant et al. (2003), but with independent data reduction. We compared our catalog and the catalog in Serjeant et al. (2003) to look for systematic differences in flux calibration and astrometry. Figure 3 shows sources in the two catalogs. Among the seven detected sources in Table 1 of Serjeant et al. (2003), six were recovered by us, despite the fact that we only included $\sim 1/4$ of the HDF-proper archival data. We failed to detect their source HDF 850.6, even though our map at its location is deeper than that of Serjeant et al. (2003). HDF 850.7 was detected in our map, but with a 979 offset. Because HDF 850.6 and HDF 850.7 are both at the map edge of Serjeant et al. (2003), where the noise is significantly higher, the disagreement between the two catalogs on these sources is not unusual. Excluding HDF 850.6 and HDF 850.7, the mean positional offset between the two catalogs is 3”, and the offsets appear to have random directions (see Fig. 3). The mean flux difference between the two catalogs is 4%. We conclude that our analysis is consistent with that of Serjeant et al. (2003) and that there is no systematic difference between our catalog and the Serjeant et al. (2003) catalog in terms of flux calibration and astrometry. We note that HDF 850.3 was detected by Hughes et al. (1998) but not by Serjeant et al. (2003) and us. HDF 850.3 is located between the negative
sidelobes of GOODS 850-10 and 19. After GOODS 850-10 and 19 were removed from the map, we found a very marginal signal (1.49 ± 0.50 mJy) at the position of HDF 850.3. This flux is only 50% of that in Hughes et al. (1998). Although it is not qualified as a detection here, HDF 850.3 may be a real source.

4.2. Jiggle Maps in Barger et al. (2000)

Barger et al. (2000) published jiggle maps targeting optically faint microjansky radio sources in the flanking fields of the HDF (Richards 2000). Their reduced maps are included in this paper and reanalyzed. There are a few differences between Barger et al. (2000) and this work. Some regions studied in that work have been further deepened since its publication. The noise estimates of Barger et al. (2000) were based on CLEANed maps in which confusion sources fainter than 3σ were not removed, while in this work the noise estimates are free from faint sources. Because of these differences, sources detected here generally have smaller errors. In Barger et al. (2000), submillimeter fluxes were measured at radio positions,
which are not necessarily flux peaks in the submillimeter map. There are eight sources with 850 \mu m S/N greater than 2.7 cataloged in Barger et al. (2000; see Fig. 3). All of them are detected in this work with S/N greater than 4.0, mostly because of the increase in depth. For these eight sources, the fluxes are in good agreement, and the mean flux ratio (Barger et al. 2000) at greater than 2.7 \sigma (all detected with more than 4 \sigma here). Diamonds are for scan-map sources in Borys et al. (2002). Thick circles are for supermap (jiggle-map plus scan map) sources at greater than 4 \sigma and thin circles for those at greater than 3.5 \sigma (Borys et al. 2003). Note the major disagreements between the jiggle-map and scan-map sources (see §§ 4.3 and 4.4).

4.3. HDF Flanking Field Scan Map

Borys et al. (2002) used the scan mode of SCUBA to survey a 125 arcmin² area with \sim 3 mJy 1 \sigma sensitivity in the flanking fields of the HDF. Our jiggle map has a survey area comparable to that of the scan map but a sensitivity up to 3 times higher. The difference between our jiggle map and the scan map of Borys et al. (2002) is quite large, even at the 4 \sigma level. All 12 scan-map sources have fluxes greater than 10 mJy, and 10 are well inside our survey area (see Fig. 3). However, only three scan-map sources in Table 1 of Borys et al. (2002) were detected by our jiggle map, and these had fairly large positional offsets. They are HDFSM 3608+1246 (associated with our source GOODS 850-8), 3620+1701 (GOODS 850-15), and 3644+1452 (GOODS 850-11). The offsets between the scan-map and jiggle-map source positions are 10".5, 12".6, and 9".9, respectively. The offsets seem to have random directions (see Fig. 3). On average, the scan-map fluxes of the three sources are 42\% greater than the jiggle-map fluxes.

We measured the jiggle-map fluxes and the associated errors at the scan-map source positions. The results are summarized in Table 2. Only the three sources mentioned above were detected at greater than 3 \sigma. We also looked for jiggle-map sources within 30" (\sim 2 times the beam FWHM), centered at the scan-map source positions. As shown in Table 2, except for the three detections, all jiggle-map sources found have either fluxes that are too low (\lesssim \frac{1}{2} of the scan-map fluxes) or offsets that are too large to be associated with the scan-map sources. We conclude that only three of the 10 scan-map sources within our field of view were detected in the jiggle map. This is a surprising result, because our jiggle map is considerably deeper than the scan map. If the scan-map sources were all real, then our jiggle map should have detected most of them.

Furthermore, we note that two very bright jiggle-map sources were not detected by the scan map. They are GOODS 850-6 and 16. GOODS 850-6 has a jiggle-map flux of 13.6 mJy at 6.01 GHz. There is a 107.0 \pm 9.6 mJy 1.4 GHz source (Richards 2000) associated with this source. GOODS 850-16 has a jiggle-map

### Table 2: Scan-Map Sources and Their Jiggle-Map Counterparts

| HDFSMM\(a\) | \(S_{\text{Scan}}\) (mJy) | \(S_{\text{Jiggle}}\) (mJy) | ID\(b\) | \(d\) (arcsec) |
|--------------|----------------|----------------|--------|--------------|
| 3606+1138    | 15.4 ± 3.4     | -1.41 ± 1.36   | GOODS 850-31 | 24.8       |
| 3608+1246    | 13.8 ± 3.3     | 5.83 ± 1.47    | GOODS 850-8   | 10.5       |
| 3611+1211    | 12.2 ± 3.0     | -2.46 ± 1.20   | GOODS 850-40  | 16.3       |
| 3620+1701    | 13.2 ± 2.9     | 4.24 ± 1.39    | GOODS 850-18  | 23.7       |
| 3621+1250    | 11.4 ± 2.8     | 2.70 ± 1.82    | GOODS 850-18  | 23.1       |
| 3730+1051    | 14.3 ± 3.2     | ...            | GOODS 850-18  | 20.2       |
| 3623+1016    | 10.3 ± 2.9     | -0.22 ± 1.40   | GOODS 850-18  | 25.6       |
| 3624+1746    | 12.6 ± 3.4     | -0.64 ± 3.04   | GOODS 850-15  | 12.6       |
| 3644+1452    | 11.4 ± 2.9     | 8.12 ± 2.39    | GOODS 850-11  | 9.9        |
| 3700+1438    | 10.1 ± 2.9     | 3.79 ± 2.46    | ...           | ...        |
| 3732+1606    | 12.1 ± 3.3     | ...            | ...           | ...        |
| 3735+1423    | 13.4 ± 3.8     | 0.79 ± 1.96    | ...           | ...        |

\(a\) Scan-map source ID in Table 1 of Borys et al. (2002).

\(b\) Jiggle-map flux measured at the scan-map source position.

\(c\) Source numbers (as in Table 1) of jiggle-map sources within 30" of the scan-map position.

\(d\) Jiggle-map flux for the nearby jiggle-map source.

\(e\) Offset between the scan-map source and the nearby jiggle-map source.
flux of 12.45 mJy at 4.32 $\sigma$. There is a 324.0 $\pm$ 18.0 $\mu$Jy 1.4 GHz source (Richards 2000) associated with this source. Therefore, in terms of the 850 $\mu$m S/N ratios and the FIR-radio correlation, these two jiggle-map sources are highly significant. Both sources are within the scan-map field of view, but neither is detected by the scan map. Thus, we conclude that there is a major discrepancy between our jiggle map and the scan map of Borys et al. (2002).

### 4.4. HDF Supermap

Borys et al. (2003) constructed an “HDF supermap” by combining the scan map of Borys et al. (2002), all the jiggle maps from Serjeant et al. (2003), and a subset of our jiggle maps described here, which were already in the JCMT archive. Given the very serious disagreement between the scan map and the jiggle map, it is not obvious to us what the combination of these two maps actually means. Nevertheless, we briefly summarize the similarity and difference between the catalogs.

Among the first 194 $\sigma$ sources in Borys et al. (2003), 14 are detected (>3 $\sigma$) in our jiggle map, with positional offsets less than the beam FWHM. The mean supermap-to-jiggle map flux ratio of these 14 sources is 0.96 $\pm$ 0.19. Of the remaining undetected sources, one is HDFS 850.6, mentioned in § 4.1, and two are associated with the undetected bright scan-map sources HDFSSM 3606+1138 and 3621+1250 (see Table 2). We extended this comparison to the full list of 3.5 $\sigma$ sources in Borys et al. (2003). Among the 34 sources, only 17 are detected in our jiggle map. We noticed that bright sources below 4 $\sigma$ are overpopulated in their catalog. Five sources have fluxes of $\geq$20 mJy, while there are no greater than 4 $\sigma$ sources with comparable fluxes. All five of these bright sources are either outside or at the edge of our jiggle map; i.e., they come from the scan map. This further enhances our conclusion in § 4.3—the scan map is inconsistent with our analysis.

### 4.5. Photometry Observations

Chapman et al. (2001) measured 850 $\mu$m fluxes of optically faint radio sources in the HDF with the photometry mode of SCUBA. Two of their targets fall in our jiggle-map field of view. The source VLA J123600+621021 has a photometry flux of 11.6 $\pm$ 3.5 mJy and a jiggle-map flux of 2.21 $\pm$ 1.68 mJy. This source is detected at 3.7 $\sigma$ in the supermap but not detected in the scan map.

The source VLA J123711+621331 is close to our GOODS 850-36, with a 4$^\prime$.2 offset. It has a photometry flux of 7.7 $\pm$ 2.4 mJy and a jiggle-map flux of 3.98 $\pm$ 1.33 mJy, at the radio position, or 4.4 $\pm$ 1.36 mJy, if the flux of HDFS 850-36 is adopted. For this source, although the detections agree with each other, there is an up to 90% difference between the photometry and jiggle-map fluxes. This source is not detected in either the scan map or the supermap. Because the two photometry detections and the jiggle-map source GOODS 850-36 are all marginal (S/N $\sim$ 3.0), the photometry results and our jiggle-map results are only marginally inconsistent. However, the large overestimates of the photometry fluxes in these cases do illustrate the danger of using 3 $\sigma$ detections in targeted photometry measurements, where one only integrates to a fixed S/N. Such a procedure will always result in overestimating the fluxes and should be avoided.

Radio source VLA J123600.2+621047 was listed in Chapman et al. (2003a), but no details about its observation were explained there or in previous papers. We found that this source was observed in photometry mode, according to the SCUBA archive. This source has a 7.9 $\pm$ 2.4 mJy photometry flux (Chapman et al. 2003a). Our jiggle-map flux at the radio position is 0.35 $\pm$ 1.5 mJy. We notice that it is 64$^\prime$ away from the negative sidelobe of GOODS 850-25. Our nondetection of VLA J123600.2+621047 might be due to the sidelobe of GOODS 850-25. However, to fully cancel a 7.9 mJy flux, GOODS 850-25 has to have a flux of at least 15.8 mJy, which is unlikely. This suggests that the 7.9 mJy photometry flux may also be an overestimate. Unfortunately, the western sidelobe of GOODS 850-25 is outside our map, and the eastern sidelobe of VLA J123600.2+621047 ($\sim$3.9 mJy, assuming the photometry flux) is below our sensitivity limit. We cannot unambiguously determine their fluxes using our jiggle map alone.

### 5. MONTE CARLO SIMULATIONS

#### 5.1. Number Counts

The differential number counts [N(S)] are determined by dividing the number of detected sources in some flux (S) interval by the area over which these sources could be detected. The differential counts of our sample can be constructed using the source catalog and the survey area summarized in Figure 4. For relatively small samples, cumulative number counts [N($>$S)], which are integrals of the differential counts, are more commonly adopted. The caution for cumulative counts is that the points are not statistically independent. Errors in the bright end of the cumulative counts propagate to the faint end, and changes in the shape of the counts may be hard to see.

In Figure 5, we present raw cumulative 850 $\mu$m counts, derived from our 3.0, 3.5, and 4.0 $\sigma$ sources. We note that sources detected at lower significance levels are not necessarily fainter in flux, because our map sensitivities are highly nonuniform. Raw counts constructed from lower significance samples are systematically higher in the plot because of spurious sources caused by noise and because of Eddington bias. At the 3.0 and 3.5 $\sigma$ levels, the Gaussian probabilities of spurious detections are $4.4 \times 10^{-3}$ and $8.7 \times 10^{-4}$, respectively. Given the $\sim$110 arcmin$^2$ survey area, which corresponds to $\sim$1600 primary beams (i.e., $\sim$1600 independent points), we estimated the numbers of spurious sources in our 3.0 and 3.5 $\sigma$ samples to be $\sim$7 and $\sim$1, respectively. We note that the Gaussian assumption is supported by the noise analysis in Cowie et al. (2002), and the above result is also consistent with our true-noise map. We used our source extraction
algorithm to find “sources” in the true-noise map. The number of spurious sources found from the true noise map above 3.0 σ is 10, consistent with the estimate based on Gaussian noise. While the spurious sources mainly affect the 3.0–3.5 σ level, the Eddington bias affects the number counts at all S/N levels. We show below that the differences between the 3.0, 3.5, and 4 σ counts are indeed consistent with each other if the effects of noise, confusion, and systematic biases, such as incompleteness and the Eddington bias, are all taken into account. To do this, we performed iterative Monte Carlo simulations to estimate these effects and to derive the number counts.

We created simulated images by randomly drawing sources from a plausible power-law number count relation onto the true-noise map. We limited the fluxes of the input sources to be between 0.2 and 25 mJy. The deepest region in our map has a 0.4 mJy rms sensitivity, so only sources brighter than 1.2 mJy can be detected in this region. Thus, the 0.2 mJy lower cutoff is sufficient for our purpose and is also consistent with the fact that most of the 850 μm EBL arises in sources brighter than 0.3 mJy (Cowie et al. 2002). The upper cutoff produces a turnover on the bright-end counts (see Fig. 6). However, the 25 mJy value used here is not important, because there are not enough sources at this flux level to tightly constrain the upper cutoff.

We used the procedures described in § 3.1 to detect the simulated sources. To derive the averaged output counts, we ran 100 realizations over the whole field (corresponding to ~3.1 deg$^2$) and detected ~3100 simulated sources at 3.5 σ. We compared the recovered 3.5 σ counts and the input power law to derive the bias with flux and used this to correct the observed 3.5 σ counts. We fitted the corrected observed counts with a power law, using the area-weighted maximum likelihood method (Crawford et al. 1970) to account for the statistical interdependence of the points in the cumulative counts. We used this fitted power law as the input for the next simulations. We repeated this process until the fitted power law from the observations matched the input power law within the fitting errors. The final number counts in the 2–10 mJy range determined by the power-law fit are

$$N(>S) = 1.09 \times 10^4 (S/\text{mJy})^{-1.76} \text{ deg}^{-2}. \quad (3)$$

We present in Figure 6 these power-law input counts (with a 25 mJy upper cutoff), the averaged output counts from the simulations, and the 3.5 σ raw counts from the observations. The 90% confidence range of the observed counts is obtained by measuring the spread of the output counts over the various realizations and is presented in Figure 6. For a convenient reference, we approximate the bias-corrected upper and lower 90% confidence ranges between 2 and 10 mJy with the power laws

$$N(>S) = 1.85 \times 10^4 (S/\text{mJy})^{-1.85} \text{ deg}^{-2}$$

and

$$N(>S) = 7.3 \times 10^4 (S/\text{mJy})^{-1.75} \text{ deg}^{-2},$$

respectively.

As mentioned above, the 3.0 σ raw counts are affected by spurious sources. However, this effect is taken into account by the use of the true-noise map. Running similar simulations on the 3.0 and 4.0 σ sources provided fitted power laws similar to that of equation (3), and the differences between these counts are well within the uncertainties. Although we used the 3.5 σ results in this paper, we note that the counts derived from the 3.0, 3.5, and 4.0 σ samples are all consistent with each other.

As shown in Figure 6, the counts are best determined in the 2–10 mJy range. The larger uncertainties at the bright and the faint ends are caused by the small numbers of sources detected at these flux ranges. Between 2.0 and 10 mJy, the recovered counts exceed the input counts because of the Eddington bias. Detections at a given flux range include fainter sources with fluxes boosted by positive noise, as well as brighter sources dimmed by negative noise. For power-law distributions with negative indices, there are more flux-boosted faint sources than dimmed bright sources. This will cause a positive systematic flux boost and an upward shift in the number counts. Over the 2.0–10 mJy range, we measured the median flux boost from the recovered counts to be 44% for the 3.5 σ counts. Eales et al. (2000) found a median flux boost factor of 44% for their sources brighter than 3 mJy, and Scott et al. (2002) found boost factors of 28% and 35% at greater than 5 mJy for their two areas, both of which are consistent with the present analysis.

At 5 and 10 mJy, the bias-corrected cumulative counts (eq. [3] and the dashed line in Fig. 6) are, respectively, $640^{+300}_{-200}$.  

![Figure 5](image1.png)

**Fig. 5.**—Cumulative 850 μm number counts derived from our 3.0 σ (dotted line), 3.5 σ (dashed line), and 4.0 σ sources (dash-dotted line). The raw counts contain complex effects of noise, confusion, and systematic biases. Although the 3.0 σ counts are affected by noise more seriously, all the 3.0, 3.5, and 4.0 σ counts are consistent with a single power law (§ 5).

![Figure 6](image2.png)

**Fig. 6.**—Results of Monte Carlo simulations. Observed counts (crosses) are from the 3.5 σ sources. Each cross in the plot represents a detected source in Table 1. The solid line is for the averaged number counts derived from the simulations that contain 100 realizations and ~3100 3.5 σ sources. Dotted lines are for the 90% confidence range for the observed counts derived from each realization. The dashed line is for the input power-law counts described in eq. (3). The input counts start to turn over above 10 mJy because of the 25 mJy upper cutoff used in the simulations. Because of the large uncertainties above 10 mJy, the upper cutoff is not constrained by the observations.
and 190_{-190}^{+70} \text{deg}^{-2}$, where the uncertainties are derived from the simulated 90% confidence ranges. This is consistent with the Scott et al. (2002) measurements of $620_{-100}^{+110}$ and $180 \pm 60 \text{deg}^{-2}$ at 5 and 10 mJy, respectively, the Eales et al. (2000) measurement of $500 \pm 200 \text{deg}^{-2}$ at 5 mJy, and the Barger et al. (1999a) measurement of $610_{-190}^{+240} \text{deg}^{-2}$ at 5 mJy. At the fainter 2 mJy end, our cumulative counts are $3220_{-1000}^{+1910} \text{deg}^{-2}$. The other determinations at 2 mJy are $3500_{-1000}^{+1500}$ (Cowie et al. 2002), $2900 \pm 1000$ (Smail et al. 2002), and $6800_{-1900}^{+2600} \text{deg}^{-2}$ (Chapman et al. 2002). Our counts are consistent with these values within the errors.

The total surface brightness of submillimeter sources can be derived from the number counts. Using the corrected counts in equation (3) and the 90% uncertainties, we found that the contribution to the 850 µm EBL in the 2–10 mJy flux range is $1.05_{-0.32}^{+0.62} \times 10^4 \text{mJy deg}^{-2}$. The percentage of the 850 µm EBL residing in this range is thus $34_{-11}^{+20}$%, if we adopt the 850 µm EBL measurement of $3.1 \times 10^4 \text{mJy deg}^{-2}$ from Puget et al. (1996), or $24_{-14}^{+36}$%, if we adopt the measurement of $4.4 \times 10^4 \text{mJy deg}^{-2}$ from Fixsen et al. (1998). Eales et al. (2000) and Webb et al. (2003b) adopted the Fixsen et al. (1998) value and found the fraction of resolved 850 µm EBL to be 19% and 13%, respectively, for bias-corrected source fluxes greater than 2 mJy. Our value of 24% is consistent with the values of those two groups within the errors.

5.2. Reliability of Source Extraction

Using the Monte Carlo simulations above, we studied the reliability of our source extraction. Here we focus on source flux, spurious detections, and positional error. Within one beam around each detected source in a simulation, we search for input sources and calculate the total flux contributed by these input sources. In Figure 7, we plot the mean output (detected)-to-input flux ratios versus S/N (solid line). To show the spread of the flux ratios, in addition to the mean flux ratios, we also plot the ±1 σ flux ratios (dashed lines). As discussed in § 5.1 (the Eddington bias), because there are more fainter sources, the mean flux ratios are always greater than 1. For the power-law number counts in equation (3), the mean flux ratio at 4 σ is 1.47, and the median for greater than 3.5 σ in the 2–10 mJy range is 1.44. We note that we did not find the flux ratios to be a strong function of flux (as opposed to S/N) because our sensitivities are highly nonuniform. For the same reason, we did not attempt to quantify the completeness with flux. The effect of completeness is already included in Figure 6 and in the derivation of equation (3) and the EBL contribution of the sources.

To derive positional errors, we first excluded detections with large output-to-input flux ratios. If the total input flux contributed less than 40% of the detected flux, we considered the detection to be spurious. There are on average 10.6 spurious detections in each realization, and 9.0 of them are less than 4 σ detections. We note that the choice of 40% is arbitrary because the distributions of source flux and noise flux are both continuous. The number of spurious detections defined in this way is very slightly larger than that from the Gaussian analysis and consistent with that in the true-noise map (see § 5.1). Among the real detections where the input fluxes contributed more than 40% of the detected fluxes, there were usually more than one input source found within the beam. Most of the input sources are faint and have fluxes of less than 1 mJy. In 83% of the real detections, one input source dominates the total input flux at the greater than 50% level. We used the brightest input source within the beam to calculate positional error, whether this brightest source dominated the total input flux or not. We plot the mean positional offsets versus S/N in Figure 7 (solid line). To show the distribution of the offsets for a given S/N, in addition to the mean offset, we also plot the ±1 σ of the offset distribution (dashed line); i.e., 84% of the detections have offsets below the ±1 σ line. For S/N of less than 6, while the mean offset is fairly small (3–4″), corresponding to about 15% of detections have offsets greater than 5″.

We note that the positional error is a consequence of noise and confusion. Therefore, the offsets are expected to be a complex function of flux and S/N. The use of the true-noise map in our simulations should provide a reasonable estimate of the effect of the noise. The effect of confusion is simulated by our input power law in equation (3), which is consistent with the observations. However, because the sensitivity is highly nonuniform across our map, we only saw the mean offsets to be a function of S/N, not as a function of flux. We also point out that the positional error presented here only accounts for the effect of noise and confusion. We can use the radio
Fig. 8.—HST ACS thumbnail images for the 4 σ sources in Table 1. The gray-scale images are summed F435, F606, F775, and F850 images, centered on the submillimeter positions. The panels are 18" on a side. North is up, and east is to the left. The submillimeter flux and uncertainty of each source are labeled at the bottom of each panel. Large circles in the panels are the error circles for the submillimeter positions. Approximately 84% of the real counterparts to the submillimeter sources should be within the error circles. Squares, crosses, and triangles are, respectively, 1.4 GHz sources, X-ray sources, and 15 μm sources with 3 σ submillimeter detections. Optical spectroscopic redshifts (three significant digits) or reliable (>80% confidence) photometric redshifts (two significant digits) are labeled. To avoid confusing the plot, we only label photometric redshifts of radio and X-ray sources and galaxies with $z > 1.0$. See Table 6 for a full list of available redshifts.

positions to test for other effects, such as the pointing error of the telescope and astrometry error (see the next section).

6. 1.4 GHz, X-RAY, AND MIR COUNTERPART CANDIDATES

In this section, we describe the 1.4 GHz and X-ray sources that are identified as candidate counterparts to the submillimeter sources. The fundamental difficulty of identifying counterparts to the submillimeter sources is the low resolution and the low S/N in the submillimeter observations. In § 5.2, we show that our source extraction could have positional errors (+1 σ) between 2" and 6", depending on the S/N. To estimate telescope pointing and astrometry errors, we offset the submillimeter map by $0''$–$10''$ to maximize the mean submillimeter fluxes of 1.4 GHz sources. We found that the maximum mean submillimeter fluxes were measured with 1" offsets in both the right ascension and declination directions. While these offsets indicate a small absolute value for the general pointing and astrometry errors for the whole map, the errors for individual jiggle maps could be larger. To account for the pointing and astrometry errors, we added a 2" rms error in quadrature onto the +1 σ offsets shown in Figure 7 and calculated the positional error for each detected submillimeter source (Table 1). The error circles are shown in Figure 8 and can be used to judge how likely a radio or X-ray source is to be the counterpart to the submillimeter source. Approximately 84% of the real counterparts should fall in the error circles. Hereafter in this paper, we restrict most of our discussion to greater than 4 σ sources because of their relatively small positional errors and more secure detections.

6.1. 1.4 GHz Counterpart Candidates and Millimetric Redshifts

There is a tight correlation between the 1.4 GHz and FIR fluxes of normal galaxies in the local universe (see, e.g., Condon 1992). For high-redshift submillimeter sources, the ratio of the submillimeter to the 1.4 GHz flux is an increasing function of redshift (Carilli & Yun 1999; Barger et al. 2000; Yun & Carilli 2002), because the thermal dust emission in the submillimeter and the nonthermal emission in the radio have different spectral slopes. However, we still anticipate that a fraction of the brighter submillimeter sources will have radio counterparts according to the FIR-radio correlation. For sources detected at both submillimeter and radio wavelengths, the redshifts can be estimated. In addition, the radio detection provides subarcsecond astrometry for the submillimeter sources because of the high resolution of radio interferometers, allowing us to identify the optical counterparts and make spectroscopic observations.

Richards (2000) presented a catalog of 372 1.4 GHz sources detected in a Very Large Array map centered on the HDF-N that covers a 40' diameter region with an effective resolution of 1'8. The 5 σ completeness limit for compact sources in the central region is 40 μJy. Eighty-seven of the sources are within our submillimeter field of view (850 μm rms sensitivity of less than 4.0 mJy). We measured the submillimeter fluxes at the positions of these radio sources and looked for 3 σ detections. Before we measured the submillimeter flux at a radio position, we removed bright submillimeter sources in Table 1 that are at least one beam FWHM away from the radio position. This minimizes the sidelobe interference of nearby bright submillimeter sources. In this way, 14 radio sources were found to have greater than 3 σ submillimeter detections. The eight submillimeter-detected radio sources in Barger et al. (2000) are all recovered here. Thirteen of the 14 submillimeter-detected

---

6 The Very Large Array is a facility of the National Radio Astronomy Observatory (NRAO). The NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
radio sources are associated with 12 (out of the 17) greater than 4 \( \sigma \) submillimeter sources; two of the radio sources are associated with one submillimeter source (GOODS 850-11). There are 13 submillimeter sources in Table 1 with \( S_{850} > 6 \) mJy and \( S/N > 4 \). Eight, or \( \sim 60\% \), have radio sources associated with them. This fraction of radio detections agrees with other analyses of bright submillimeter sources (Barger et al. 2000; Ivison et al. 2002; Chapman et al. 2003b). The offsets between the radio positions and the beam-optimized submillimeter positions are all within 9"\(^{\prime}\), with a vector mean offset of 1\(^{\prime\prime}\)38. Nine of the 13 radio sources have offsets less than or comparable to the positional uncertainties of the submillimeter sources. We summarize these radio sources in Table 3 and Figure 8.

In order to understand the fraction of random 1.4 GHz sources in these nine counterpart candidates, we made estimates based on the surface density of 1.4 GHz sources and Monte Carlo simulations. Using the 40–1000 \( \mu \)Jy number counts in Richards (2000), we calculated that 0.019 and 0.043 1.4 GHz sources will be found within a 6" (roughly corresponding to our largest error circle) and a 9" circle, respectively, if the distribution of 1.4 GHz sources is random. Since there are 17 submillimeter sources (\( S/N > 4 \)), \( \sim 0.3 \) and 0.7 random radio sources will be found within 6" and 9" of the submillimeter source positions, respectively. In addition to the above surface density analysis, we repeated a large number of simulations in which we randomly shifted the radio sample and measured the submillimeter fluxes at the shifted radio positions. On average, 0.9 radio sources per simulation have submillimeter fluxes greater than 3 \( \sigma \), consistent with the surface density analysis. Thus, there is a good chance that \( \sim 1 \) of the 14 radio sources identified here is a chance projection. However, most of the radio sources within the \( \sim 6" \) submillimeter error circles are very likely connected to the submillimeter sources in various ways. Most are probably the real counterparts of the submillimeter sources, but they could also be sources in the same groups as the submillimeter sources or sources lensed by the same foreground objects.

If we assume that the radio sources are the true counterparts of the submillimeter sources, we can crudely estimate the redshifts of the submillimeter sources, using their submillimeter-to-radio SEDs (Yun & Carilli 2002) or simply their submillimeter-to-radio flux ratios (Carilli & Yun 1999; Barger et al. 2000). Using this millimeter redshift technique, we estimated the redshifts of the 14 submillimeter sources described above. We used the formula

\[
z + 1 = 0.98(S_{850}/S_{1.4})^{0.26},
\]

which was derived using the Arp 220 template (Barger et al. 2000). The 850 \( \mu \)m fluxes are the beam-optimized fluxes in Table 1. The results are listed in Table 3. For the two radio sources associated with submillimeter source GOODS 850-11, we assumed that only one radio source is responsible for the submillimeter emission and calculated its submillimeter-to-radio flux ratio. If both radio sources are responsible for the submillimeter emission, then the redshifts in Table 3 are overestimated. We also discuss GOODS 850-11 in \( \S \) 7.1. The errors in the redshifts in Table 3 only account for the errors in the 850 \( \mu \)m and 1.4 GHz fluxes. The actual uncertainty of this redshift estimate comes from the uncertainty in the submillimeter-to-radio SED model and could be larger than 0.5 (see, e.g., Ivison et al. 2002).

### 6.2. X-Ray Counterpart Candidates

We searched for X-ray counterparts to the 850\( \mu \)m sources, using the CDF-N 2 Ms point-source catalog of Alexander et al. (2003). We used a searching method identical to that for the radio identifications, but we excluded X-ray sources that are more than 10" away from the nearest submillimeter source. This is because the density of X-ray sources at the center of the ACS field is considerably higher than the density of radio sources, and the probability of chance projections is higher. Twenty X-ray sources were found in this way. Fifteen X-ray sources are

| R.A., Dec.* | \( S_{1.4} \) | IDsubmm | \( z^c \) | \( d^d \) |
|-------------|-------------|---------|-------|-------|
| (J2000.0)   | \( (\mu \text{Jy}) \) |         |       | (arcsec) |
| 12 36 51.76, 62 12 21.30° | \( 49.3 \pm 7.9 \) | GOODS 850-1 | \( 2.28 \pm 0.16 \) | 6.0 |
| 12 36 22.65, 62 16 29.74° | \( 70.9 \pm 8.7 \) | GOODS 850-2 | \( 2.57 \pm 0.16 \) | 8.6 |
| 12 36 18.33, 62 15 50.48° | \( 151.0 \pm 11.0 \) | GOODS 850-3 | \( 1.73 \pm 0.11 \) | 3.9 |
| 12 37 30.80, 62 12 58.98° | \( 107.0 \pm 9.6 \) | GOODS 850-6 | \( 2.45 \pm 0.17 \) | 4.3 |
| 12 36 16.15, 62 15 13.67° | \( 53.9 \pm 8.4 \) | GOODS 850-7 | \( 2.37 \pm 0.20 \) | 3.8 |
| 12 37 07.21, 62 14 08.08° | \( 45.3 \pm 7.9 \) | GOODS 850-9 | \( 2.64 \pm 0.23 \) | 5.6 |
| 12 36 49.71, 62 13 12.78° | \( 49.7 \pm 9.9 \) | GOODS 850-10 | \( 1.76 \pm 0.17 \) | 6.9 |
| 12 36 46.05, 62 14 48.69° | \( 124.0 \pm 9.8 \) | GOODS 850-11 | \( 2.13 \pm 0.18 \) | 2.1 |
| 12 36 46.76, 62 14 45.45° | \( 117.0 \pm 9.6 \) | GOODS 850-11 | \( 2.18 \pm 0.18 \) | 7.8 |
| 12 36 56.60, 62 12 07.62° | \( 46.2 \pm 7.9 \) | GOODS 850-12 | \( 1.96 \pm 0.21 \) | 6.2 |
| 12 36 21.27, 62 17 08.40° | \( 148.0 \pm 11.0 \) | GOODS 850-15 | \( 1.83 \pm 0.18 \) | 4.1 |
| 12 37 00.26, 62 09 09.75° | \( 324.0 \pm 18.0 \) | GOODS 850-16 | \( 1.53 \pm 0.16 \) | 5.9 |
| 12 36 29.13, 62 10 45.79° | \( 81.4 \pm 8.7 \) | GOODS 850-17 | \( 1.96 \pm 0.20 \) | 2.6 |
| 12 37 11.34, 62 13 31.02° | \( 132.0 \pm 10.1 \) | GOODS 850-36 | \( 1.44 \pm 0.20 \) | 4.2 |

**TABLE 3**

1.4 GHz Counterpart Candidates

---

\* Source coordinates and 1.4 GHz fluxes from Richards (2000).

\* Associated 850 \( \mu \)m source.

\* Angular separation between the radio positions and the submillimeter positions.

\* These radio sources may not be the real counterparts to the submillimeter emission. See discussion in \( \S \) 7.1.
associated with the 10 (out of 17) submillimeter sources with S/N > 4. Three submillimeter sources (GOODS 850-7, 11, and 13) have multiple X-ray sources associated with them. Eight of the X-ray sources are associated with radio sources, all with positional offsets less than 0.6 between the radio and X-ray positions (see Fig. 8). The submillimeter-detected X-ray sources are summarized in Table 4 and Figure 8.

The mean X-ray source surface density in the central 5 arcminutes, and arcseconds. Because there are 17 4 σ submillimeter sources searched, the above possibility suggests that ~3 of the 15 X-ray sources around the 4 σ submillimeter sources are chance projections. In addition, by randomly shifting the X-ray sample, we find that the mean number of submillimeter-detected random X-ray sources is 2.7, consistent with the surface density analysis. The fraction of bright submillimeter sources (with $S_{850} > 6 \text{ mJy}$ and S/N > 4) with X-ray counterparts is ~50%. However, if the number of random sources is taken into account, the fraction decreases to ~35%. Thus, radio sources are generally more likely to provide an astrometric measurement of the submillimeter source position than X-ray sources and much less likely to provide a spurious identification.

### 6.3. MIR Counterpart Candidates

Using the above methods, we searched for MIR counterparts to the 850 μm sources in the main catalog of Aussel et al. (1999), which made use of the Infrared Space Observatory 6.75 and 15 μm data. Six MIR sources are found to have 850 μm fluxes greater than 3 σ and are associated with five submillimeter sources (Table 5). All of them are 15 μm sources, and only one has a detected 6.75 μm flux. The offsets between the MIR and submillimeter positions are between 3″ and 10″. We also estimated the number of random MIR sources based on the 15 μm source number counts in Aussel et al. (1999). The surface density of 15 μm sources brighter than 100, μJy is ~7 × 10^3 deg^-2, corresponding to ~0.19 random sources per 10^9 radius circle. There are ~10 850 μm sources within the MIR field of view. Thus, we expect that one or two of the six MIR counterpart candidates are chance projections. By randomly shifting the MIR sample, we find that the mean number of submillimeter-detected random MIR sources is 1.5, consistent with the surface density analysis. Despite the comparable number counts, the fraction of chance projections for MIR sources is much higher than that for X-ray sources, because the MIR observations are around the HDF proper, which has the highest density of detected 850 μm sources. We note that all of the MIR sources with redshifts in Table 5 are at $z < 1.0$, significantly lower than the millimetric or photometric redshifts of the submillimeter sources (see § 7.1). We discuss these individual sources in § 7.1.

### 7. Optical Counterpart Candidates and Redshifts

A ground-based, wide-field, deep, multicolor imaging survey centered on the HDF-N was conducted by Capak et al. (2004). Accurate photometry and astrometry data in the U, B, V, R, I, and z’ bands, covering 0.2 deg^-2, and additional HK’-band data, over a smaller region covering the CDF-N, are available. Using these data, P. Capak et al. (2004, in preparation) derived photometric redshifts of the galaxies in the HDF, based on the Bayesian technique in Benitez (2000). Here we use the photometry and photometric redshift data for an overview of the 850 μm source counterpart candidates, as
redshifts are 95% errors (see Benítez 2000 and P. Capak et al. 2004, in preparation).

| ID       | R.A.     | Decl.     | U⁺ | B⁺ | V⁺ | R⁺ | I⁺ | z⁺ | HK⁺ | Notes  |
|----------|----------|-----------|----|----|----|----|----|----|-----|--------|
| GOODS 850-1a | 12 36 52.11 | 62 12 26.46 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-1b | 12 36 51.90 | 62 12 25.82 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-1c | 12 36 51.73 | 62 12 20.42 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-2a | 12 36 22.62 | 62 16 21.28 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-2b | 12 36 22.61 | 62 16 29.58 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-3a | 12 36 19.30 | 62 15 47.78 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-4a | 12 36 38.64 | 62 12 04.25 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-4b | 12 36 38.82 | 62 13 13.37 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-5a | 12 36 33.25 | 62 14 11.22 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-5b | 12 36 33.52 | 62 14 18.14 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-6a | 12 37 30.69 | 62 13 03.50 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-6b | 12 37 30.47 | 62 13 02.84 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-7a | 12 37 30.77 | 62 12 58.00 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-7b | 12 37 29.92 | 62 13 00.94 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-8a | 12 37 31.56 | 62 13 05.76 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-8b | 12 36 16.14 | 62 15 14.00 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-9a | 12 37 08.26 | 62 14 05.49 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-9b | 12 37 06.66 | 62 14 00.16 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-9c | 12 37 07.21 | 62 14 08.15 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-10a | 12 36 49.45 | 62 13 16.70 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-10b | 12 36 50.50 | 62 13 16.28 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-10c | 12 36 49.73 | 62 13 13.15 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-11a | 12 36 46.16 | 62 14 51.77 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-11b | 12 36 46.07 | 62 14 48.89 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-11c | 12 36 46.75 | 62 14 46.15 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-11d | 12 36 45.65 | 62 14 51.57 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-11e | 12 36 46.90 | 62 14 47.47 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-12a | 12 36 55.81 | 62 12 00.94 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-12b | 12 36 56.34 | 62 11 57.94 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-13a | 12 37 13.02 | 62 12 09.54 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-13b | 12 37 14.31 | 62 12 08.60 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-14a | 12 36 22.98 | 62 13 17.01 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-15a | 12 36 20.92 | 62 17 09.45 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-16a | 12 37 00.45 | 62 09 17.74 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |
| GOODS 850-17a | 12 36 29.16 | 62 10 47.31 | 97 | 97 | 97 | 97 | 97 | 97 | 97 |        |

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

**a** All magnitudes are in the AB system. The 5 or limiting magnitudes for U, B, V, R, I, z, and HK are, respectively, 27.1, 26.9, 26.8, 26.6, 25.6, 25.4, and 22.1.

**b** Spectroscopic redshifts (three significant digits) or photometric redshifts (two significant digits) with greater than 80% confidence. The errors of photometric redshifts are 95% errors (see Benítez 2000 and P. Capak et al. 2004, in preparation).

**c** Data from Wirth et al. (2004).

**d** Data from Cowie et al. (2004).

**e** Data from Cowie et al. (2004).

**f** Data from Barger et al. (2003).
1.3 mm had located the dust continuum between the optical sources. We refer to Downes et al. (1999) and Serjeant called HDF 850.1 and is among the best-studied submillimeter source in the HDF-proper region (previously lists the optical and NIR magnitudes and redshifts of selected sources. If a photometric redshift coincides with the millimetric redshift, the identification may be more secure. Table 6 lists the optical and NIR magnitudes and redshifts of selected galaxies that are inside the positional error circles of the submillimeter sources or are associated with the radio, X-ray, and MIR sources. Galaxies in Table 6 are labeled in Figure 8. In Figure 8, we use the HST ACS images (Giavalisco et al. 2004) for their higher resolution. All magnitudes in this paper are in the AB system, where $m_{AB} = 8.90 - 2.5 \log(S/\text{Jy})$.

### 7.1. Individual Sources

Now we briefly comment on each of the 4 $\sigma$ sources. The fluxes quoted after the source names are their 850 $\mu$m fluxes. **GOODS 850-1** (5.12 $\pm$ 0.47 mJy).—This is the brightest submillimeter source in the HDF-proper region (previously called HDF 850.1) and is among the best-studied submillimeter sources. We refer to Downes et al. (1999) and Serjeant et al. (2003) for more detailed discussions of the identification of this source. An IRAM interferometric observation at 1.3 mm had located the dust continuum between the optical galaxies 1a and 1b in Figure 8 (Downes et al. 1999). This rules out the radio and X-ray source (and perhaps the MIR source, too) 1c at $z = 0.300$ (Wirth et al. 2004) as the counterpart to the submillimeter source. The IRAM position coincides with a 4.5 $\sigma$ detection at 8.5 GHz (Richards et al. 1998) and further strengthens the identification. The red galaxy 1a has a photometric redshift of 0.93. Galaxy 1b has a photometric redshift of 1.27 and an arclike morphology, suggesting that it may be lensed by 1a (Downes et al. 1999; Serjeant et al. 2003). Dunlop et al. (2004) claimed that the submillimeter source is a faint object behind galaxy 1a at $z \approx 4$. Using equation (4) and the 40 $\mu$Jy detection limit at 1.4 GHz, the nondetection at 1.4 GHz implies a redshift lower limit of $\sim 2.4$, consistent with a similar estimate made by Serjeant et al. (2003) using the 8.5 GHz flux. This lower limit does not completely rule out 1b as the counterpart to the submillimeter emission because of the uncertainties in the millimetric and photometric redshifts. **GOODS 850-2** (10.26 $\pm$ 1.21 mJy).—A radio and X-ray source (2b) could be associated with the submillimeter source. However, the offset between the radio and submillimeter positions is $8^\prime 6$, more than 2 times greater than the positional error corresponding to the submillimeter S/N. Thus, 2b is not likely to be the counterpart to the submillimeter source. Another galaxy (2a) within the error circle has a photometric redshift of $1.71^{+0.3}_{-0.4}$ and a fairly flat spectrum from $U$ to $z'$, and perhaps $HK'$, consistent with an irregular or starburst galaxy at $z > 1.3$. Indeed, the HST ACS image shows an irregular morphology and fuzzy light around the galaxy, which might be tidal features. Since 2a is closer to the submillimeter center and has a starburst and interaction signature, it could be a better counterpart candidate than 2b. However, if 2a were the real starbursting counterpart at $z = 1.7$ and Arp 220—like, its 1.4 GHz flux would be $\gtrsim 200 \mu$Jy, which would have been detected easily. If 2b is not the real counterpart to GOODS 850-2, then its nondetection in the radio suggests that the lower limit of its redshift is $\sim 3.0$. **GOODS 850-3** (7.72 $\pm$ 1.02 mJy).—A radio source could be associated with GOODS 850-3, with a millimetric redshift of 1.73. An optical galaxy (3a) with an irregular morphology, a flat $U$-to-$z'$ spectrum, and a photometric redshift of 1.72 is another possibility. Approximately $17^\prime$ to the northwest of the radio source, there are three galaxies (not labeled in Fig. 8) in the ACS image that appear to be interacting with each other. These galaxies are not resolved in the ground-based images, and their combined optical SED has a photometric redshift of $1.25^{+0.45}_{-0.4}$, with 80% confidence. This photometric redshift is consistent with the millimetric redshift but is reliable only if the three galaxies are at the same redshift. If this is the case, then the interacting group of galaxies and the radio source may be the source of the submillimeter emission. **GOODS 850-4** (8.62 $\pm$ 1.27 mJy).—An MIR source is associated with a $V = 22.83$ regular spiral galaxy at $z = 0.848$ (4b; Wirth et al. 2004). If the submillimeter emission had come from the star formation in this spiral galaxy and the galaxy had obeyed the FIR-radio correlation, the corresponding 1.4 GHz emission would have been detected. In addition, the 8.62 mJy 850 $\mu$m flux of GOODS 850-4 corresponds to an ultraluminous $\lesssim 10^{13}$ $L_\odot$ infrared luminosity. It is highly unlikely that an ultraluminous infrared galaxy has an undisturbed spiral morphology. There is a fainter galaxy (4a) inside the error circle with a photometric redshift of 3.35. This redshift is consistent with the nondetection in the radio. **GOODS 850-5** (12.94 $\pm$ 2.14 mJy).—The brightest optical galaxy inside the error circle (5a) has a spectroscopic redshift of 1.345 (Wirth et al. 2004). If this galaxy were the optical counterpart to the submillimeter source, its 1.4 GHz flux would be greater than 400 $\mu$Jy. The nondetection in the radio for GOODS 850-5 sets the lower limit of the redshift to be $\sim 3.4$. An X-ray source (5b) $8^\prime 7$ to the north of the submillimeter position has a spectroscopic redshift of 3.408 (Cohen et al. 2000), consistent with the above lower limit. Galaxy 5b

| ID       | $z_{mm}$ | $z_{opt}$ |
|----------|----------|-----------|
| GOODS 850-1 | >2.4     | ...       |
| GOODS 850-2 | >3.0     | ...       |
| GOODS 850-3 | 1.73     | 1.25      |
| GOODS 850-4 | >3.0     | 3.35      |
| GOODS 850-3 | >3.0     | 1.63      |
| GOODS 850-5 | >1.9?    | ...       |
| GOODS 850-6 | >1.6     | ...       |
| GOODS 850-7 | 1.96     | ...       |
| GOODS 850-8 | >2.8     | 3.147     |
| GOODS 850-9 | >3.2     | ...       |
| GOODS 850-10 | 1.83    | 1.64      |
| GOODS 850-11 | 1.53     | ...       |
| GOODS 850-12 | 1.96     | 1.013     |

* Millimetric redshifts derived from eq. (4). Lower limits are estimated for submillimeter sources that are not detected in radio. Also see text.

* Optical redshifts. Redshifts with four significant digits are spectroscopic redshifts. Redshifts with three significant digits are photometric redshifts with greater than 80% confidence.
and the X-ray source could be the source of the submillimeter emission.

**GOODS 850-6 (13.60 ± 2.26 mJy).**—This submillimeter source is the brightest one in our sample. The $V = 22.17$ galaxy 6d has a spectroscopic redshift of 0.512 (Cowie et al. 2004). Two galaxies (not labeled) around 6d have morphologies similar to lensed arcs. Galaxy 6d could be a gravitational lens. This lens candidate is also noted in Fassnacht et al. (2004). Galaxy 6a has a red color and a photometric redshift of 0.74. A radio source is associated with 6c, which does not have a reliable photometric redshift but has a millimetric redshift of 2.45. Galaxy 6b has a photometric redshift of 0.14 and thus is less likely the counterpart to the submillimeter source.

**GOODS 850-7 (6.20 ± 1.05 mJy).**—Two X-ray sources and one radio source are associated with this submillimeter source. Source 7a was detected in the ACS and ground-based image but is too faint for a reliable photometric redshift. If the radio source is the counterpart to the submillimeter source, the millimetric redshift is 2.37.

**GOODS 850-8 (8.13 ± 1.40 mJy).**—No optical counterpart candidates could be identified within the error circle. The only bright galaxy slightly to the north of the error circle (not labeled) has a photometric redshift of 0.10 and is not likely to be the counterpart to the submillimeter source. The nondetection in the radio sets a redshift lower limit of 2.9.

**GOODS 850-9 (7.05 ± 1.22 mJy).**—Two galaxies near the error circle (9a and 9b) have photometric redshifts greater than 3.0. If either of these two galaxies is the submillimeter source, the redshift of greater than 3 will be consistent with the nondetection in the radio. Galaxy 9c is a radio and X-ray source and has a photometric redshift of 1.63. The millimetric redshift of 9c is 2.64.

**GOODS 850-10 (2.63 ± 0.47 mJy).**—The radio, X-ray, and MIR sources appear to be associated with galaxy 10c, which has a spectroscopic redshift of 0.475 (Wirth et al. 2004). Because of its low redshift, galaxy 10c may not be the counterpart to the submillimeter source. In addition, the millimetric redshift derived from the submillimeter and radio flux is 1.76. Thus, it is very likely that the radio source is not associated with the submillimeter source and that the millimetric redshift is wrong. There are two other bright galaxies, 10a and 10b, inside the error circle, with redshifts of 1.20 and 0.851, respectively (Cohen et al. 2000). If any of these $z \sim 1.0$ galaxies were the submillimeter source, its 1.4 GHz flux would be greater than 100 $\mu$Jy and would have been detected. The lack of 1.4 GHz detection sets a lower limit of 1.9 to the millimetric redshift. A similar problem was noted by Serjeant et al. (2003). The lack of a radio detection for 10a and 10b and the inconsistency between the spectroscopic and millimetric redshifts of 10c leave no obvious identification for GOODS 850-10.

**GOODS 850-11 (10.82 ± 2.22 mJy).**—Its submillimeter flux is among the higher ones in the HDF, and there is a high density of sources in this region. Two radio sources, three X-ray sources, and two MIR sources are associated with GOODS 850-11. Two optically bright galaxies (11a and 11e) are at redshifts of 0.680 (Wirth et al. 2004) and 0.556 (Cowie et al. 2004). Galaxy 11e appears to be the closest counterpart candidate to one MIR source whose MIR position is slightly outside Figure 8. All other radio, X-ray, and MIR sources are either not detected in the optical or are too faint to obtain reliable photometric redshifts. These sources, as well as GOODS 850-11, might be in the same group as 11a or 11e, but they are more likely at higher redshifts. In § 6.1, we used either only 11b or only 11c to calculate the millimetric redshift of GOODS 850-11 and obtained a result of 2.13 or 2.18, respectively. If both radio sources are in the same group and are Arp 220–like, their redshifts will be 1.64, based on the total 1.4 GHz and submillimeter fluxes, and their physical separation will be ≈35 kpc ($H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.73$, $\Omega_L = 0.27$). Either redshift (1.6 or 2.1) is significantly higher than the redshifts of 11a and 11e, suggesting that galaxies 11a and 11e could act as lenses on the background submillimeter, radio, X-ray, and MIR sources. However, radio sources 11b and 11c are not likely multiple images of one object, because of their different optical colors (Table 6). We note that 11c appears to be the brighter member of an interacting pair of galaxies.

**GOODS 850-12 (3.26 ± 0.69 mJy).**—Two galaxies inside the error circle appear to have similar photometric redshifts of $\sim$1.7. Galaxy 12a is resolved in the ACS image and has an irregular morphology. An optically faint radio source is 6.2′ away from the submillimeter position. If this radio source is the counterpart to the submillimeter source, its millimetric redshift is 1.96.

**GOODS 850-13 (7.03 ± 1.53 mJy).**—Two X-ray sources are associated with GOODS 850-13. Source 13b has a spectroscopic redshift of 3.147 (Barger et al. 2003) and a red NIR-optical color. The other X-ray source is optically faint. The brighter galaxy (13a) has a redshift of 0.556 (Wirth et al. 2004) and is less likely to be the counterpart to the submillimeter source, because of its low redshift.

**GOODS 850-14 (10.46 ± 2.32 mJy).**—This is an optically faint submillimeter source. The brightest galaxy inside the error circle (14a) has $V = 26.18$ and no reliable photometric redshift. The bright galaxy outside the error circle (not labeled) has a photometric redshift of 0.12 and therefore is less likely to be the source of the submillimeter emission. The nondetection in the radio sets a lower limit of 3.2 to its millimetric redshift.

**GOODS 850-15 (8.69 ± 1.98 mJy).**—The radio source associated with GOODS 850-15 is optically faint and has a millimetric redshift of 1.83. The radio source is marginally resolved by the interferometer and has a 2″5 FWHM (Richards 2000). A galaxy (15a) with a photometric redshift of 1.64 is 2″6 to the west of the radio source and may be physically connected to the radio source. This galaxy also shows signatures of interaction with a faint galaxy at $\sim$0′78 to its north. In the radio map there is a $\sim$32 mJy peak associated with this galaxy, which is slightly below the 40 $\mu$Jy detection limit and therefore not cataloged in Richards (2000). This hint of radio emission suggests that the galaxy is a starbursting galaxy. Given the proximity of the radio source and galaxy 15a and the coincident optical and millimetric redshifts, galaxy 15a and the radio/submillimeter source are likely to be in the same group of galaxies, at a redshift between 1.6 and 1.8.

**GOODS 850-16 (12.45 ± 2.88 mJy).**—An optically faint radio source is associated with GOODS 850-16. It has a millimetric redshift of 1.53. Galaxy 16a is the brightest galaxy within the error circle and has a photometric redshift of 0.70. It is not likely to be the source of the submillimeter emission.

**GOODS 850-17 (5.72 ± 1.38 mJy).**—The radio source and the X-ray source coincide with a pair of interacting galaxies at $z = 1.013$ (Cohen et al. 2000). This pair of galaxies is likely also the source of the submillimeter emission. The millimetric redshift is 1.96. The difference between the spectroscopic and millimetric redshifts is somewhat larger than we might expect.
indicating that this radio and submillimeter source is not Arp 220–like.

7.2. Redshifts of the Sources

In Table 7, we summarize the redshifts of the most plausible candidates or the redshift lower limits discussed above. For sources with both millimeter and photometric redshifts, we use the photometric ones, given their relatively lower uncertainties. Excluding those with only lower limits, the median redshift of 11 possibly identified sources is 2.0. Including the lower limits set by the radio nondetections, the lower limit of the median redshift is 2.4. This 2.4 lower limit is consistent with Ivison et al. (2002) and Chapman et al. (2003a) but is considerably greater than the lower limit of 1.4 in Webb et al. (2003a, 2003b). The analyses of all these groups, including ours, intensively use radio images. The 1.4 GHz radio image used here and in Ivison et al. is significantly deeper than that in Webb et al., so Webb et al. can only detect radio emission from sources at lower redshifts (see, e.g., their Table 6). This may be the origin of the difference. Lilly et al. (1999) presented eight submillimeter sources and their spectroscopic and photometric redshifts. Their sources are optically (i band) identified on the basis of positional coincidence. Four of their sources have \( z < 1 \), and the others have \( 1 < z < 3 \). Only two of their sources have 5 GHz radio counterparts. The significant fraction of their sources at \( z < 1 \) is very different from those measured by all the other groups mentioned above. This may be due to misidentifications caused by the higher surface density of optically bright galaxies at lower redshifts.

The above comparison clearly illustrates the limitation of our current observational techniques. While pure optical identifications are biased toward low-redshift (\( z \leq 1 \)) and optically bright galaxies, radio identifications can accurately locate the submillimeter emission and are capable of finding optically faint submillimeter sources at much higher redshifts (\( z \leq 2.5 \)). On the other hand, the sensitivities of current radio interferometers still limit the highest redshift that we can reach. To identify sources at even higher redshifts, we will need either more sensitive radio observations to detect the redshifted nonthermal emission or submillimeter interferometric imaging to directly locate the submillimeter emission. The latter is now becoming possible with the advent of the Submillimeter Array (Moran 1998).

8. SUMMARY

1. We have carried out an 850 \( \mu \)m survey with SCUBA on the JCMT of an \( \sim 110 \) arcmin\(^2\) area centered on the HDF-N, with 1 \( \sigma \) sensitivities of 0.4–4 mJy. Our source catalog is fully consistent with previous jiggle-map studies. However, there is a serious discrepancy between our jiggle map and the scan map of Borys et al. (2002). There is also marginal inconsistency between our jiggle map and the photometry studies of Chapman et al. (2001, 2003a).

2. After taking into account the effects of noise, confusion, incompleteness, and the Eddington bias using Monte Carlo simulations, we find that the observed cumulative 850 \( \mu \)m source number counts between 2 and 10 mJy are consistent with a single power law \( N(>S) = 1.09 \times 10^4 (S/rmJy)^{-1.76} \) deg\(^{-2}\). Our number counts are also consistent with previous measurements in blank fields and lensing cluster fields. In the 2–10 mJy flux range, the integrated submillimeter source surface brightness accounts for 34\(^{+20\%}\)-11\% or 24\(^{+14\%}\)-14\% of the FIR EBL, depending on which measurement of the FIR EBL is adopted.

3. Radio, X-ray, and MIR counterpart candidates are identified near the submillimeter source positions. From surface density analyses and Monte Carlo simulations, the numbers of random sources around the submillimeter sources are estimated. The results suggest that most of these counterpart candidates are physically connected to the submillimeter sources and are not chance projections along the line of sight.

4. The radio counterparts are used to estimate the redshifts of the submillimeter sources by assuming the Arp 220 SED. Optical counterpart candidates are also selected around the submillimeter sources or at the radio and X-ray positions. Spectroscopic and photometric redshifts are also used, if available. For 11 possibly identified sources, the median redshift is 2.0. Using the lower limits provided by the radio nondetections, we find a lower limit of 2.4 for the median redshift of 17 sources. Identifications of submillimeter sources at higher redshifts have to await the advent of high-resolution submillimeter imaging or more sensitive radio imaging.

We thank Peter Capak for useful discussions about the optical and NIR photometry and for kindly providing us with the photometric redshift data in advance of publication. We thank the referee, Steve Eales, for the comprehensive report that improved the manuscript and Colin Borys for communicating with us about the SCUBA noise artifact and the JCMT tracking error. W.-H. W. and L. L. C. gratefully acknowledge support from NASA grants GO2-3187B and HST-G0-09425.03-A and NSF grant AST 00-84816. A. J. B. gratefully acknowledges support from NSF grants AST 00-84847, AST 02-39425, NASA grant HST-G0-09425.30-A, the University of Wisconsin Research Committee, with funds granted by the Wisconsin Alumni Research Foundation, the Alfred P. Sloan Foundation, and the David and Lucile Packard Foundation.

REFERENCES

Alexander, D. M., et al. 2003, AJ, 126, 539
Aussel, H., Cesarsky, C. J., Elbaz, D., & Stark, J. L. 1999, A&A, 342, 313
Barger, A. J., Cowie, L. L., & Richards, E. A. 2000, AJ, 119, 2092
Barger, A. J., Cowie, L. L., & Sanders, D. B. 1999a, ApJ, 518, L5
Barger, A. J., Cowie, L. L., Sanders, D. B., Fulton, E., Taniguchi, Y., Sato, Y., Kawara, K., & Okuda, H. 1998, Nature, 394, 248
Barger, A. J., Cowie, L. L., Smail, I., Ivison, R. J., Blain, A. W., & Kneib, J.-P. 1999b, AJ, 117, 2656
Barger, A. J., et al. 2003, AJ, 126, 632
Benitez, N. 2000, ApJ, 536, 571
Bertoldi, F., et al. 2000, A&A, 360, 92
Blain, A. W., & Longair, M. S. 1993, MNRAS, 264, 509
Borys, C., Chapman, S. C., Halpern, M., & Scott, D. 2002, MNRAS, 330, L63
———, 2003, MNRAS, 344, 385
Carilli, C. L., & Yun, M. S. 1999, ApJ, 513, L13
Capak, P., et al. 2004, AJ, 127, 180
Chapman, S. C., Blain, A. W., Ivison, R. J., & Smail, I. R. 2003a, Nature, 422, 695
Chapman, S. C., Richards, E. A., Lewis, G. F., Wilson, G., & Barger, A. J. 2001, ApJ, 548, L147
Chapman, S. C., Scott, D., Borys, C., & Fahlman, G. 2002, MNRAS, 330, 92
Chapman, S. C., et al. 2003b, ApJ, 585, 57
Cohen, J. G., Hogg, D. W., Blandford, R., Cowie, L. L., Hu, E., Songaila, A., Shopbell, P., & Richberg, K. 2000, ApJ, 538, 29
Condon, J. J. 1992, ARA&A, 30, 575
Cowie, L. L., Barger, A. J., Hu, E. M., Capak, P., & Songaila, A. 2004, AJ, 127, 3137
Cowie, L. L., Barger, A. J., & Kneib, J.-P. 2002, AJ, 123, 2197
No. 2, 2004

850 μm SCUBA SURVEY OF HDF-N

671

Crawford, D. F., Jauncey, D. L., & Murdoch, H. S. 1970, ApJ, 162, 405
Downes, D., et al. 1999, A&A, 347, 809
Dunlop, J. S., et al. 2004, MNRAS, 350, 769
Eales, S., Bertoldi, F., Ivison, R., Carilli, C., Dunne, L., & Owen, F. 2003, MNRAS, 344, 169
Eales, S., Lilly, S., Gear, W., Dunne, L., Bond, J. R., Hammer, F., Le Fèvre, O., & Crampton, D. 1999, ApJ, 515, 518
Eales, S., Lilly, S., Webb, T., Dunne, L., Gear, W., Clements, D., & Yun, M. 2000, AJ, 120, 2244
Fassnacht, C. D., Moustakas, L., Casertano, S., Ferguson, H. C., Lucas, R. A., & Park, Y. 2004, ApJ, 600, L155
Fixsen, D. J., Dwek, E., Mather, J. C., Bennett, C. L., & Shafer, R. A. 1998, ApJ, 508, 123
Fox, M. J., et al. 2002, MNRAS, 331, 839
Giavalisco, M., et al. 2004, ApJ, 600, L93
Gispert, R., Lagache, G., & Puget, J. L. 2000, A&A, 360, 1
Hauser, M. G., et al. 1998, ApJ, 508, 25
Hughes, D. H., et al. 1998, Nature, 394, 241
Ivison, R. J., et al. 2002, MNRAS, 337, 1
Jennes, T., & Lightfoot, J. F. 2000, Starlink User Note 216 (Chilton: CLRC)
Lilly, S. J., Eales, S. A., Gear, W. K. P., Hammer, F., Le Fèvre, O., Crampton, D., Bond, J. R., & Dunne, L. 1999, ApJ, 518, 641
Moran, J. M. 1998, Proc. SPIE, 3357, 208
Puget, J.-L., Abergel, A., Bernard, J.-P., Boulanger, F., Burton, W. B., Désert, F.-X., & Hartmann, D. 1996, A&A, 308, L5
Richards, E. A. 2000, ApJ, 533, 611
Richards, E. A., Keeler, M. I., Fomalont, E. B., Windhorst, R. A., & Partridge, R. B. 1998, AJ, 116, 1039
Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 749
Scott, S. E., et al. 2002, MNRAS, 331, 817
Serjeant, S., et al. 2003, MNRAS, 344, 887
Smail, I, Ivison, R. J., & Blain, A. W. 1997, ApJ, 490, L5
Smail, I, Ivison, R. J., Blain, A. W., & Kneib, J.-P. 2002, MNRAS, 331, 495
Webb, T. M., Lilly, S. J., Clements, D. L., Eales, S., Yun, M., Brodwin, M., Dunne, L., & Gear, W. K. 2003a, ApJ, 597, 680
Webb, T. M., et al. 2003b, ApJ, 587, 41
Wirth, G. D., et al. 2004, AJ, 127, 3121
Yun, M. S., & Carilli, C. L. 2002, ApJ, 568, 88