FIRST CONSTRAINTS ON SOURCE COUNTS AT 350 μm

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ABSTRACT

We have imaged a ~6 arcmin² region in the Bootes Deep Field using the 350 μm—optimized second-generation Submillimeter High Angular Resolution Camera (SHARC II), achieving a peak 1 σ sensitivity of ~5 mJy. We detect three sources above 3 σ, and determine a spurious source detection rate of 1.09 in our maps. In the absence of 5 σ detections, we rely on deep 24 μm and 20 cm imaging to deduce which sources are most likely to be genuine, giving two real sources. From this we derive an integral source count of 0.84 ± 0.39 sources arcmin⁻² at S > 13 mJy, which is consistent with 350 μm source count models that have an IR-luminous galaxy population evolving with redshift. We use these constraints to consider the future for ground-based short-submillimeter surveys.

Subject headings: infrared: galaxies — galaxies: high-redshift — galaxies: starburst — submillimeter

Online material: color figures

1. INTRODUCTION

Toward the end of the last decade, a new population of submillimeter-selected galaxies (SMGs) were discovered through pioneering lensed and blank surveys using the 850 μm—optimized Submillimeter Common User Bolometer Array (SCUBA; Holland et al. 1999) at the James Clerk Maxwell Telescope (Smail et al. 1997; Hughes et al. 1998; Barger et al. 1998; Eales et al. 1999). Extensive follow-up observations constrained the population to be mainly massive star forming galaxies (see, e.g., Fox et al. 2002; Blain et al. 2002; Borys et al. 2003) at high redshift (z ~ 2; Chapman et al. 2005), with the bulk of the luminosity emitted in the rest-frame far-IR, although the detection of these sources had not been predicted by semi-analytical hierarchical models (for instance, contrast the order of magnitude spread in the models of Guiderdoni et al. [1997] with the SCUBA-constrained single model of Guiderdoni et al. [1998]). SMGs can be thought of as the high-redshift counterparts of the luminous and ultraluminous infrared galaxies (LIRGs and ULIRGs14) found in the local universe (the majority selected with the Infrared Astronomical Satellite [IRAS]; Soifer et al. 1984, 1987; Joseph & Wright 1985). The first surveys with SCUBA paved the way for many similar surveys using other submillimeter detectors (e.g., MAMBO, BOLOCAM, etc.; Bertoldi et al. 2000; Laurent et al. 2005). These surveys were mostly limited to long submillimeter through millimeter wavelengths (500–1300 μm), tracing emission on the long-wavelength side of the peak at typical redshifts. The commissioning of the 350 μm—optimized Second Generation Submillimeter High Angular Resolution Camera (SHARC II; Dowell et al. 2003) at the Caltech Submillimeter Observatory (CSO), currently the largest ground-based submillimeter bolometer array (Moseley et al. 2004), provided a feasible opportunity to carry out a blind survey in this wave band.

Using SHARC II, we targeted a ~6 arcmin² region in the Bootes Deep Field (de Vries et al. 2002) for a blank, deep survey, which was designed to select LIRGs and ULIRGs through their far-IR thermal dust emission (measured near the peak of the spectral energy distribution [SED]) at 1<z<3, the epoch of peak cosmic star formation rate density (see, e.g., Hopkins & Beacom 2006). The survey, achieving a peak 1 σ sensitivity of ~5 mJy, produced a promising result, as we reported the discovery of the first galaxy selected at 350 μm (SMM J143206.65+341613.4, also named Short Submillimeter Galaxy 1 [SSG 1]; Khan et al. 2005). The discovery of SSG 1 raises a number of questions regarding the nature of galaxies detected in the short-submillimeter wave bands (200–500 μm). Given the demanding observational requirements (good 350 μm atmospheric transmission from Mauna Kea is ~30%, as opposed to ~80% at 850 μm; Serabyn et al. 1998), short-submillimeter surveys would be a poor use of ground-based telescope time if they traced the same population as did long-submillimeter surveys. However, follow-up 1.2 mm
imaging appears to confirm the assertions of Khan et al. (2005) that deep short-submillimeter observations can probe SMGs too faint for selection in longer submillimeter bands (faint SMGs), whose global properties might differ from the bright SMG population (e.g., lower redshift, warmer dust temperatures, lower luminosities; S. A. Khan et al. 2007, in preparation). Given the paucity of 350-μm–selected sources, the most efficient way to characterize the nature of the population is through deriving source counts and analyzing the models that best fit the data. This complements the multiwavelength analysis on individual sources that was begun in other survey publications (Khan et al. 2005, 2007 in preparation; Khan 2006).

In this paper we present the first constraints on the source counts at 350 μm. We outline our observation program design, data reduction, and analysis methodology. We discuss the criteria for selecting candidate 350 μm sources and the determination of the number of spurious sources in the map. From this we derive the measured source counts from the survey. We discuss how the counts reflect the nature of our sources and conclude with the implications for future blank surveys in the short-submillimeter wave bands.

2. OBSERVATION PROGRAM

Submillimeter surveys have followed three approaches: using gravitational lensing around clusters (e.g., Smail et al. 1997), selecting fields surrounding known high-redshift sources (e.g., high-redshift quasars; Ivison et al. 2000), and targeting a region of blank sky (e.g., Hughes et al. 1998). For a given integration time, the number of detected sources will be higher in a lensing cluster survey than in a blank survey, due to the brightness magnification. However, this approach is highly dependent on the cluster mass distribution, which can produce significant systematic uncertainties on the luminosity function of the detected population and its evolution. Even in the best possible case (a smooth cluster), imprecision in the cluster model could still dominate over the behavior of the source counts. Submillimeter surveys centered on known high-redshift sources run a risk of being redshift biased, since these are typically found at other wavelengths, and many are lensed. In addition, correlation analyses show a higher probability of finding enhanced source counts over typical survey sizes in such areas (see Lagache et al. 2005, and references therein).

To avoid the uncertainties associated with the biases listed above, we have chosen to pursue a blank survey, which can be implemented in ways ranging from deep, small area to shallow, large area surveys. In order to maximize the number of detections in the survey, we could discriminate between the two approaches using the following argument: the differential number versus flux relationship can be approximated locally as

$$N(S) \approx k_d(S/S_0)^{-\gamma} \text{[sources sr}^{-1} \text{mJy}^{-1}],$$

(1)

where $N(S)$ describes the overall surface density of galaxies as a function of flux density $S$. For a given limiting flux, $S_{\text{min}}$, the number of sources is

$$N(>S_{\text{min}}) = \int_{S_{\text{min}}}^{\infty} \frac{dN}{dS} dS \Rightarrow N(>S_{\text{min}}) \propto S_{\text{min}}^{1-\gamma}. \quad (2)$$

During a single pointed observation, the noise is expected to integrate down as $t^{-1/2}$. Hence, the number of detected sources, $N$, is related to the integration time $t$ via

$$N_{\text{deep}} \propto t^{(\gamma-1)/2}. \quad (3)$$

If the integration time were instead subdivided into an equal number of shallower observations, this would yield

$$N_{\text{wide}} \propto t. \quad (4)$$

Therefore, a deep pointing yields more detections per exposure than a wider, shallow survey, as long as the flux density sensitivity remains at a level where $\gamma > 3$. For a non-evolving Euclidean universe $\gamma = 2.5$, but current constraints on the submillimeter galaxy population show evolution ($\gamma > 2.5$) for a broad range of brighter flux densities (e.g., Coppin et al. 2006). Constraining $\gamma$ through direct observation requires the detection of tens of sources at 350 μm—a huge demand on telescope time.

Rather than parameterize the source counts from very small data sets, a more practical approach is to discriminate between existing source counts models, in particular those that successfully reproduce the IR-submillimeter counts. Using the models in the literature at the time of the survey (Franceschini et al. 1994; Guiderdoni et al. 1998b; Pearson 2001; Takeuchi et al. 2001), the target 1σ sensitivity was based on where the models begin to show significant deviations in their source count predictions, with the majority of models having $\gamma > 3$. This threshold was $1\sigma = 5$ mJy.

2.1. Observations

SHARC II is a 350-μm–optimized camera built around a 12 × 32 element close-packed bolometer array. It achieves a point-source sensitivity of $\sim 1$ Jy s$^{-1/2}$ in good weather. The 384 pixels of the SHARC II array image a region of around 1.0′ × 2.6′ on the sky. Its filled absorber array provides instantaneous imaging of the entire field of view, sampled at roughly 2.5 pixels per nominal beam area.

The 350-μm window is a difficult one for observers: the in-band atmospheric opacity $\tau$ is rarely $<0.8$, with signal-to-noise ratio $S/N \propto e^{-\tau}/(1-e^{-\tau})^{1/2}$, making efficient observations extremely weather dependent. For ground-based far-IR/submillimeter observations, the variation in atmospheric emission is the dominant noise source over all temporal frequencies. Although rapid image differencing, commonly called chopping, is used to remove the atmospheric signal, this technique can give rise to a $\sqrt{2}$ increase in noise and a loss of observing time from a chopping duty cycle of $<1$. Furthermore, chopping does not adequately remove portions of the atmospheric signal that vary more rapidly than the chop frequency, something that our data reduction analysis has shown to exist (Khan 2006).

The design of SHARC II eliminates the need to chop. Atmospheric noise is spatially correlated, implying that the spatial variation in the atmosphere occurs in the line of sight of several pixels. By scanning the detector array over the target region, the celestial signal—spatially fixed and constant in time—will be mapped by several detector pixels. This scanning technique allows the determination of the individual pixel gains and offsets, and the removal of the atmospheric signal on all timescales; least-squares fitting can also model other instrumental contributions, alongside the simultaneous derivation of the celestial sky map and associated uncertainty. Although this modeling will induce some covariance between adjacent map pixels, this is small compared to the dominant contribution from photon noise. As part of the commissioning phase of SHARC II, we tested a number of Lissajous scan patterns, typically using smaller amplitude sweeps of about 15′′ in the x-direction (perpendicular to the 32 rows) and 10″–20″ in the y-axis.15 This ensured that the entire area was

15 The amplitude : period ratio should not be much larger than 1.4″ s$^{-1}$.  

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well covered, with substantial redundancy between detector pixels and map pixels.

The survey was awarded 12 half-nights of observing time, commencing in 2003 January. From that, just under 7 hr of good-quality data (from observations done in reasonable weather in 2004 January and March) were obtained, centered on the Boötes Deep Field (de Vries et al. 2002) at position R.A. = 14h32m5.75s, decl. = 34°16′47.5″ (J2000). For these data the in-band zenith atmospheric opacity (\(\tau_{350\mu m}\)) ranged from 1.0 to 1.4, corresponding to a zenith transmission of around 30%. The beam profile was measured on known compact sources, and was verified to be within 3% of the diffraction-limited beam width of 8.5″. All observations were taken using the Dish Surface Optimization System (Leong et al. 2006), which corrects for the primary mirror deformation as a function of zenith angle, to improve the telescope efficiency and the pointing.

2.2. Data Reduction and Source Extraction

The data were reduced using the standard CSO reduction software, CRUSH (Kovács 2006) version 1.40a8, using the advised reduction parameters for deep observations. This software implements a self-consistent least-squares algorithm to solve for the celestial emission, taking into account instrumental and atmospheric contributions to the signal. Forty individual scans, each representing approximately 10 minutes of integration time and all centered on the Boötes Deep Field position, were reduced simultaneously through CRUSH. The output, the CRUSH-reduced skymap, was calibrated with the flux density and point-spread function (PSF) based on observations of Callisto taken throughout the observing period at similar elevations (usually every hour). The flux density of Callisto was derived from the CSO SHARC II calibrator catalog. A thorough treatment of the reduction methodology, with detailed explanations of the reduction parameters, can be found in Khan (2006).

For each pixel in the CRUSH-reduced skymap, a least-squares fit for a point source was determined. From the CRUSH celestial map, for each skymap pixel \(j\), a submap comprising all pixels within 16.2″ (or 10 CRUSH skymap pixels), was extracted. The size of the submap was chosen to provide a good determination of the source and background, but not so large as to require a more complicated background model, whereby four parameters were fit simultaneously: source intensity, mean background, and both a horizontal and vertical linear gradient. The Callisto PSF was then applied to this model in a weighted least-squares fit; this is roughly equivalent to smoothing the celestial map with the PSF (see Fig. 1). For each pixel, this fit produces an intensity \(S_j\) and an associated

![Fig. 1.— Point-source intensity (top left) and noise maps (top right) from the least-square fit to the CRUSH reduced map (Jy beam\(^{-1}\)). The bottom panels show the adjusted significance map (left) and the map pixels with \(\xi > 2.8\) (right). [See the electronic edition of the Journal for a color version of this figure.]](image-url)
statistical uncertainty, $\sigma_j$, in units of flux density per beam. These values allowed an estimate of the approximate S/N, which we refer to as the “significance” ($\xi_j$), using

$$\xi_j = S_j / \sigma_j.$$  \hspace{1cm} (5)

This fitting reproduces the known 350 $\mu$m flux densities of standard calibration sources to within the calibration uncertainties, but for faint sources, the map noise is the dominant uncertainty.

### 2.3. Reweighting the Map

In a map with few detections, the expected distribution of $\xi$ will be Gaussian, with a variance of 1, centered on zero. We define

$$\Xi = \sqrt{\frac{\sum \xi^2}{N}},$$  \hspace{1cm} (6)

the rms variation in $\xi$.

For the Boötes data, $\Xi = 1.51$, implying further noise terms not accounted for in the CRUSH analysis. While it is possible $\Xi > 1$ could be due to real structure in the maps (such as confusion noise, the statistical variation from unresolved sources), this is unlikely given the expected number of detections based on the survey sensitivity (using the models in § 2). Other models to derive an appropriate scaling factor were considered, from a simple constant offset to treating the excess noise as additional variance that is added in quadrature to the statistical uncertainty from the detector noise using maximum likelihood statistics (see Khan 2006), but an adequate solution was to simply scale the map by $\Xi$:

$$\sigma'_j = \Xi \sigma_j,$$  \hspace{1cm} (7)

giving a corrected significance of $\xi'_j = \xi_j / \Xi$. The magnitude of $\Xi$ appears stable with the integration time: real structure in the sky should be $t^{1/2}$ more significant for longer integrations. For source counts, the systematics associated with this excess noise are small compared to Poisson statistics. From this point, $\xi$ and $\sigma$ refer to the adjusted values, $\xi'$ and $\sigma'$. The adjusted significance distribution in the map is shown in Figure 2, alongside the corresponding survey coverage for the adjusted noise (Fig. 3). It is this adjusted noise that is used for source extraction.\hspace{1cm} \hspace{1cm} (6)

### 2.4. Extracted Source Properties

The corrected significance was used to select candidate detections, where $|\xi| \geq 3$. There were three positive sources that met the detection criteria, including the previously reported SSG 1 (Khan et al. 2005; Khan 2006), summarized in Table 1 (note: $\sigma$ and $\xi$ are scaled by $\Xi$), and two negative.

The variation of $\chi^2$ with source position gives the position confidence contour, as given in Table 1, quoting 3 $\sigma$ positional uncertainties (the best-fitting $\chi^2$ position will not necessarily match the peak S/N position, as illustrated by SSG 3 in Table 1).

### 3. CONSTRAINTS ON THE 350 $\mu$m—SELECTED POPULATION

The relation between the measured density of sources and the corresponding flux densities (the source counts) constrains theoretical models of the source luminosity function and its evolution. A thorough treatment of the measured counts would include a variety of statistical processes (e.g., confusion noise, errors in the map). But the small number of detections in this survey means that Poisson noise is dominant.

Even in the absence of real sources ($\mu_3$), there will be still a statistical chance of detecting a source above the $\xi \geq 3$ $\sigma$ threshold. The mean number of these detections in the entire survey is called the accidental rate, $\mu_A$ (also referred to as the spurious source detection rate). If the expected number of 350 $\mu$m sources,
both real and spurious, is small, then the two types of detections can be considered as independent detection processes, giving the total number of detections as \( \mu = \mu_A + \mu_S \).

3.1. Empirical Estimate of the Accidental Rate

A standard approach to determining the accidental rate is by using the pixel-pixel covariance to produce a model for the expected number of connected regions that lie above the detection threshold (3 \( \sigma \)), assuming that these covariances are well characterized. If the map noise obeyed Gaussian statistics, the probability of a pixel having S/N \( \geq 3 \sigma \) per beam would be 0.00135. The approximate number of map beams is 310 (using the Callisto PSF). Thus, the expected number of accidental sources would be \( \mu_A \approx 0.4 \). In the real CRUSH-reduced map, however, the difficulty in characterizing the noise (§2.3) shows that it is not Gaussian, which forces use of an alternative method for determining \( \mu_A \). One way is an empirical approach, similar to that used in Serjeant et al. (2003), based on the fact that sky noise is not correlated with celestial position \((\alpha, \delta)\) but real astronomical sources are.

For each raw data scan, a random rotation\(^{17}\) angle was assigned, and the entire data set with rotation angles was passed to CRUSH for reduction. This has the effect of smearing the true astronomical sources while keeping the spatially correlated noise intact. The source-extraction method of §2.2 was used to determine the number of candidate sources in the rotated maps. In total, 634 rotated maps were generated this way. Although the corrupted-astrometry maps have slightly different area-sensitivity coverage than the original map, the uncorrupted map is a random sample from this wider ensemble. The original map coverage is typical of the corrupted sample. The excess noise \( \Sigma \) of the original map is also within the range found for the corrupted maps (1.23–1.59).

The corrupted-astrometry maps produce the greatest density of spurious sources in the low-coverage, high-noise regions. However, all the candidate 3 \( \sigma \) sources in Table 1 are in the central region, where \( \sigma \leq 10 \) mJy. In this region, the spurious source detection rate is Poisson distributed with an expectation of \( 1.09 \pm 0.04 \).\(^{18}\)

With three candidate point sources and an accidental rate of 1.09, the true detection rate is poorly determined. However, observations at other wavelengths can assist in determining which observations at other wavelengths can assist in determining which sources are real. Although this introduces a selection bias, it will be small compared to Poisson statistics. Two of the candidate sources in Table 1 are \( > 5 \sigma \) detections at 24 \( \mu \)m and \( > 4 \sigma \) at 20 cm. The probability of coincident detection at 24 \( \mu \)m is 0.3 and 3% for SSG 1 and 2, respectively. At 20 cm the accidental detection probability is 1% for both sources. Given these high-likelihood identifications, it is unlikely that either of these two are spurious.

SSG 3 is more problematic: the sensitivity of the 24 \( \mu \)m data suffices to detect 850 \( \mu \)m–selected galaxies (see, e.g., Egan et al. 2004). The nondetection of this source at 24 \( \mu \)m and 20 cm suggests that it is an atypical SMG, possibly at high redshift (see, e.g., Ivison et al. 2002, 2007; although without the radio/24 \( \mu \)m identification and photometric redshift estimate can be obtained). But with the expectation of 1.09 spurious sources and the multiwavelength identifications of SSG 1 and SSG 2, we assume that SSG 3 is least likely to be genuine, and so exclude it from further analysis.

3.2. Survey Completeness

To determine the survey completeness, the two real sources, SSG 1 and SSG 2 (or SMM J143206.65+341613.4 and SMM J143206.11+341648.4), were removed from the CRUSH-reduced skymap and a source of random intensity was inserted into the no-source skymap, randomly placed over the entire skymap area, \( A \). The simulated-source map was then fit as in §2.2, and the fraction of simulated sources recovered at \( \geq 3 \sigma \) was determined through a Monte Carlo simulation (with the noise scaled by the same \( \Sigma \) as the original map). The completeness against simulated source flux density is shown in Figure 3, for the deepest part of the map (\( \sigma \leq 10 \) mJy).

3.3. Source Counts

The number of sources detected by a survey in area \( A \) to depth \( S > S_{\text{min}} \) will be

\[
N_{\text{det}} = A \int_{S_{\text{min}}}^{\infty} N(S) \times C(S) \, dS, \tag{8}
\]

where \( C(S) \) is the completeness within the survey area. Typical source count models (e.g., those given in §2) are well represented by power laws in flux density, as given by equation (1). Setting \( N_{\text{det}} = 2 \), substituting equation (1) for \( N(S) \), and normalizing the differential counts at \( S_0 = 20 \) mJy gives \( k_2 \approx 0.035 \) sources \( \text{arcmin}^{-2} \text{mJy}^{-1} \). The normalization at 20 mJy gives the least dependence of \( k_2 \) on \( \gamma \) for the present survey, less than 10% variation for 2.5 \( \leq \gamma \leq 4.0 \).

The uncertainties on \( k_2 \) are set by Poisson statistics. For an observed count of two objects, the true counts are between 0.53 and 5.32 with 90% confidence (Gehrels 1986). The uncertainty on \( k_2 \) scales directly with these values. Equation (2) allows direct comparison with integral count models. We choose \( S_{\text{min}} = 13 \) mJy, again minimizing the dependence on \( \gamma \) for the actual survey, and find 0.84\(^{+1.30}_{-0.62}\) sources \( \text{arcmin}^{-2} \) with \( S > 13 \) mJy (as shown in Fig. 4), quoting the 90% confidence uncertainty. The variation is <5% for 2.5 \( \leq \gamma \leq 4.0 \).

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\(^{17}\) The rotation angle is a parameter intended to represent the position angle of the SHARC II array on the sky. For our present purposes, introducing a random value is nothing more than a simple method of offsetting the array astrometry from its true value.

\(^{18}\) The uncertainty is in the measurement of the accidental rate, not the range in the number of accidental sources.

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\( \text{Table 1} \)

| Candidate Source | Flux Density (mJy beam\(^{-1}\)) | Peak Significance (\( \sigma \)) | R.A. (J2000.0) | Decl. (J2000.0) |
|------------------|-------------------------------|------------------------------|----------------|----------------|
| SSG 1.............. | 23.2±6.5                      | 3.6                          | 14 32 06.65 ± 0.26 | +34 16 13.4 ± 3.4 |
| SSG 2.............. | 17.1±5.4                      | 3.2                          | 14 32 06.11 ± 0.28 | +34 16 48.4 ± 3.2 |
| SSG 3.............. | 19.9±7.1                      | 3.0                          | 14 32 07.46 ± 0.39 | +34 17 19.3 ± 8.1 |

Note.—Positional uncertainties are 3 \( \sigma \) Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

\* This confidence region is affected by the close proximity of two spurious sources with \( -3.6 \) and \( -2.2 \) \( \sigma \).
In a map with few 3σ detections, a careful consideration of the Eddington bias must be applied (e.g., Eddington 1913). Because there are usually more sources immediately below the flux limit than immediately above it, more sources are scattered above this limit, by positive noise fluctuations, than are scattered downwards to below it. Therefore, sources close to but above the flux limit have measured flux densities biased high, on average. But if we assume a form for the source counts, the effect of Eddington bias is implicitly corrected. The deboosted individual flux densities will be given in a future paper (S. A. Khan et al. 2007, in preparation).

4. DISCUSSION

The derived integral counts are presented alongside a variety of source count models from the literature in Figure 4. The models represent two approaches to source count modeling: backward evolution (C. P. Pearson 2007, in preparation; M. Vaccari et al. 2007, in preparation; Lagache et al. 2005; Pearson 2001; Rowan-Robinson 2001) and semianalytical (Guiderdoni et al. 1998b). See Hauser & Dwek (2001) for an explanation and detailed descriptions of these methodologies. The 350 μm population, like other submillimeter-selected populations, is evolving with redshift, with numbers more than an order of magnitude higher than no-evolution predictions. At 90% confidence we are able to reject the no-evolution model, as well as the no-ULIRG model from Guiderdoni et al. (1998b). But due to the small sample size, the bulk of the 350 μm models cannot yet be discriminated or rejected.

The small area of this survey means the source counts will inevitably be affected by cosmic variance. However, the number of 5σ 24 μm detections within the SHARC-Boötes area compared to the counts of Papovich et al. (2004) suggest an under-density in this field (S. A. Khan et al. 2007, in preparation). Also, the photometric redshifts of the two detected sources (z ~ 1 and z ~ 2; S. A. Khan et al. 2007, in preparation) make it unlikely that these objects are related to each other.

For comparison, we plot the 450 μm counts from Smail et al. (2002) in Figure 4, assuming an Arp 220 SED template to transform the 450 μm counts to 350 μm (the 450 μm flux density of 10 mJy being roughly equivalent to a 350 μm flux density of ~16 mJy). Although this is a crude shift, it appears consistent with the 350 μm counts. These counts are also consistent with the 350 μm limits (at ~25 mJy) on 850 μm-selected sources presented in K. Coppin et al. (2007, in preparation).

Using the relation of Fixsen et al. (1998), the intensity of the cosmic infrared background (CIB) at 350 μm is 0.65 MJy sr⁻¹. From the source counts we estimate resolving ~30% of the 350 μm background at 13 mJy (with the entire 350 μm background being resolved at a flux density of ~0.5 μJy). Although this is roughly double the fraction resolved by the Smail et al. (2002) survey at S_{350} = 16 mJy (see also Lagache et al. 2005), the counts are extremely steep in this flux density domain, and thus small increases in sensitivity result in large changes in the resolved fraction.

S. A. Khan et al. (2007, in preparation) will discuss the spectral energy distributions of the two sources detected and show that the luminosities are ~10^{12} L_☉, and the dust temperatures are in the range 30–40 K, placing them in the region of luminosity–dust temperature space between local IR-luminous galaxies and the colder, more luminous, and much more massive SCUBA sources (Blain et al. 2004). This supports the argument of Khan et al. (2005) that the short-submillimeter might sample a warmer SMG population. Indeed, the upper limits at 1200 μm (S. A. Khan et al. 2007, in preparation) imply that the SHARC II sources may lie below the detection limit of the SCUBA instrument at 850 μm. Given that this survey resolves a larger fraction of the short-submillimeter background than does the 850 μm–bright sample of Smail et al. (2002), it is possible that faint SMGs outnumber SCUBA-bright sources (defining a faint SMG as S_{850} ~ 5 mJy).

In order to better understand the nature of the short-submillimeter population, it will be necessary to increase the number of sources, sampling a larger dynamic range in flux density. This can be achieved through follow-up imaging of SMGs selected at long-submillimeter wavelengths (e.g., Kovács et al. 2006; K. Coppin et al. 2007, in preparation), or through deep surveys similar to this one. But a far more efficient way would be through space-based and balloon-borne surveys.

ESA’s Herschel Space Observatory (due for launch in ~2008; Pilbratt 2003; Harwit 2004) will carry out both medium and deep surveys in the short-submillimeter wavelengths (250, 350 and 500 μm) with the SPIRE instrument (Griffin et al. 2004). Similarly, the Balloon-borne Large Area Submillimeter Telescope (BLAST; Devlin et al. 2004) will conduct deep, large area surveys at submillimeter wavelengths, including 350 μm. These surveys will select large numbers of sources, making it possible to assess the relative contribution of bright and faint SMGs to the short-submillimeter background, and determine, through multi-wavelength analysis, whether the global properties of the short-submillimeter population are different from the SCUBA-bright SMG population.

However, the turnover in the 350 μm differential counts is predicted to occur in the flux density range 5 < S_{350} < 20 mJy (e.g., Lagache et al. 2004; C. P. Pearson 2007, in preparation; M. Vaccari et al. 2007, in preparation), which is below the 20 beams...
per source confusion limit (~21 mJy) for the *Herschel SPIRE* wavebands (BLAST will also be confusion-limited at flux densities ≤25 mJy; C. P. Pearson 2007, in preparation). This is a powerful diagnostic for discriminating both evolutionary models and the sources dominating the 350 μm background (sub-"L" galaxies that will dominate the CIB and the volume-averaged star formation rate); hence, ultradeep ground-based 350 μm surveys could be the only plausible opportunity to detect this break for the foreseeable future, with the same argument applying to surveys in other short-submillimeter bands, e.g., 450 μm with SCUBA 2 (Holland et al. 2006).

5. CONCLUSIONS

The SHARC-Boötes survey is a ~6 arcmin² blank-field survey that achieves a peak 1 σ 350 μm sensitivity of ~5 mJy. Having accounted for artificial sky structure in the map, we detect three candidate sources with S/N ≥ 3 σ. From our three detections, we use a Monte Carlo simulation to deduce a spurious source detection rate, which is Poisson distributed with an expectation of 1.09 within the central region of the map. Deep 24 μm and 20 cm imaging is used to confirm the detections and exclude spurious sources. From this identification in other bands, and with a likelihood of one source being accidental, we believe that there are two real 350 μm—selected sources in our survey.

Our source count indicates that the IR-luminous population at 350 μm is evolving with redshift, with the no-evolution scenario rejected at 90% confidence. Future 350 μm surveys with BLAST, and after that, *Herschel*, may be unable to probe sources below our current survey detection threshold (due to the constraints of source confusion) where the differential counts are expected to turn over; therefore, future ground-based observations should be designed to constrain this break through ultradeep surveys.

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REFERENCES

Barger, A. J., et al. 1998, Nature, 394, 248
Bertoldi, F., et al. 2000, A&A, 360, 92
Blain, A. W., Chapman, S. C., Smail, I., & Ivison, R. 2004, ApJ, 611, 52
Blain, A. W., Smail, I., Ivison, R. J., & Kneib, J.-P. 2002, Phys. Rep., 369, 111
Borys, C., Chapman, S. C., Halpern, M., & Scott, D. 2003, MNRAS, 344, 385
Chapman, S. C., Blain, A. W., Smail, I., & Ivison, R. J. 2005, ApJ, 622, 772
Coppi, K., et al. 2006, MNRAS, 372, 1621
Devlin, M. J., et al. 2004, Proc. SPIE, 5498, 42
de Vries, W. H., Morganti, R., Rottgering, H. J. A., Vermeulen, R., van Breugel, W., Rengelink, R., & Jarvis, M. J. 2002, AJ, 123, 1784
Dowell, C. D., et al. 2003, Proc. SPIE, 4855, 73
Eales, S., et al. 1999, ApJ, 515, 518
Eddington, A. 1913, MNRAS, 73, 359
Egami, E., et al. 2004, ApJS, 154, 130
Fixsen, D. J., et al. 1998, ApJ, 508, 123
Fox, M., et al. 2002, MNRAS, 331, 839
Franceschini, A., Mazzui, P., de Zotti, G., & Danese, L. 1994, ApJ, 427, 140
Gehrels, N. 1986, ApJ, 303, 336
Griffin, M. L., Swinyard, B. M., & Vigroux, L. 2004, Proc. SPIE, 5487, 413
Guiderdoni, B. 1998a, in ASP Conf. Ser. 146, The Young Universe: Galaxy Formation and Evolution at Intermediate and High Redshift, ed. S. D’Odorico, A. Fontana, & E. Giallongo (San Francisco: ASP), 283
Guiderdoni, B., Hivon, E., & Bouchet, F. R. 1997, in Extragalactic Astronomy in the Infrared, ed. G. A. Mamon, T. X. Thuan, & J. T. T. Van (Paris: Editions Frontieres), 521
Guiderdoni, B., Hivon, E., Bouchet, F. R., & Maffei, B. 1998b, MNRAS, 295, 877
Harwit, M. 2004, Adv. Space Res., 34, 568
Hauser, M. G., & Dwek, E. 2001, ARA&A, 39, 249
Holland, W. S., et al. 1999, MNRAS, 303, 659
———. 2006, Proc. SPIE, 6275, 45
Hopkins, A. M., & Beacom, J. F. 2006, ApJ, 651, 142
Hughes, D., et al. 1998, Nature, 394, 241
Ivison, R. J., Dunlop, J. S., Smail, I., Dey, A., Liu, M. C., & Graham, J. R. 2000, ApJ, 542, 27
Ivison, R. J., et al. 2002, MNRAS, 337, 1
———. 2007, preprint (astro-ph/0702544)
Joseph, R. D., & Wright, G. S. 1985, MNRAS, 214, 87
Khan, S. A. 2006, PhD thesis, University of London
Khan, S. A., et al. 2005, ApJ, 631, L9
Kovács, A. 2006, PhD thesis, Caltech
Kovacs, A., Chapman, S. C., Dowell, C. D., Blain, A. W., Ivison, R. J., Smail, I., & Phillips, T. G. 2006, ApJ, 650, 392
Lagache, G., Puget, J.-L., & Dole, H. 2005, ARA&A, 43, 727
Lagache, G., et al. 2004, ApJS, 154, 112
Laurent, G. T., et al. 2005, ApJ, 623, 742
Leong, M., Peng, R., Houde, M., Yoshida, H., Chamberlin, R., & Phillips, T. G. 2006, Proc. SPIE, 6275, 21
Moseley, S. H., Allen, C. A., Benford, D., Dowell, C. D., Harper, D. A., Phillips, T. G., Silverberg, R. F., & Staguhn, J. 2004, Nucl. Instrum. Methods Phys. Res. A, 520, 417
Papovich, C., et al. 2004, ApJS, 154, 70
Pearson, C. P. 2001, MNRAS, 325, 1511
Pilbratt, G. L. 2003, Proc. SPIE, 4850, 586
Rowan-Robinson, M. 2001, Proc. SPIE, 4855, 73
Serjeant, S., et al. 2003, MNRAS, 344, 887
Smail, I., Ivison, R. J., & Blain, A. W. 1997, ApJ, 490, 359
Smail, I., Ivison, R. J., Blain, A. W., & Kneib, J.-P. 2002, MNRAS, 331, 495
Soifer, B. T., Neugebauer, G., & Houck, J. R. 1987, ARA&A, 25, 187
Soifer, B. T., et al. 1984, ApJ, 278, L71
Takeuchi, T., et al. 2001, PASJ, 53, 37