RADIO AND MID-INFRARED IDENTIFICATION OF BLAST SOURCE COUNTERPARTS IN THE CHANDRA DEEP FIELD SOUTH

SIMON DYE1, PETER A. R. ADE1, JAMES J. BOCK2, EDWARD L. CHAPIN3, MARK J. DEVLIN4, JAMES S. DUNLOP5, STEPHEN A. EALES6, MATTHEW GRIFFIN6, JOSHUA O. GUARDSEN6, MARK HALPERN3, PETER C. HARGRAVE3, DAVID H. HUGHES7, JEFF KLEIN8, BENJAMIN MAGNELLI9, GAELEN MARSDEN3, PHILIP MAUSKOPF10, LORENZO MONCELS11, CALVIN B. NETTERFIELD12,10, LUCA OLMI11,12, ENZO PASCALE1, GUILLAUME PATANCHON13, MARIE REX14, DOUGLAS SCOTT13, CHRISTOPHER SEMISCH4, TOM TARGETT1, NICHOLAS THOMAS6, MATTHEW D. P. TRUCH4, CAROLE TUCKER1, GREGORY S. TUCKER14, MARCO P. VIERO9, AND DONALD V. WIEBE3

1 Cardiff University, School of Physics & Astronomy, Queens Buildings, The Parade, Cardiff, CF24 3AA, UK
2 Jet Propulsion Laboratory, Pasadena, CA 91109-8099, USA
3 Department of Physics & Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T 1Z1, Canada
4 Department of Physics & Astronomy, University of Pennsylvania, 209 South 33rd Street, Philadelphia, PA, 19104, USA
5 Institute for Astronomy, University of Edinburgh, Royal Observatory, Edinburgh, EH9 3HJ, UK
6 Department of Physics, University of Miami, 1320 Campo Sano Drive, Coral Gables, FL 33146, USA
7 Instituto Nacional de Astrofísica Óptica y Electrónica (INAOE), Apartado Postal 51 y 72000 Puebla, Mexico
8 Laboratoire AIM, CEA/DSM-CNRS-Université Paris Diderot, IRFU/Service d’Astrophysique, Bât. 709, CEA-Saclay, F-91191 Gif-sur-Yvette Cedex, France
9 Department of Astronomy & Astrophysics, University of Toronto, 50 St. George Street Toronto, ON M5S 3H4, Canada
10 Department of Physics, University of Toronto, 60 St. George Street, Toronto, ON M5S 1A7, Canada
11 Physics Department, University of Puerto Rico, Rio Piedras Campus, Box 23343, UPR station, Puerto Rico
12 INAF, Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125, Firenze, Italy
13 Université Paris Diderot, Laboratoire APC, 10, rue Alice Domon et Léonie Duquet 75205 Paris, France
14 Department of Physics, Brown University, 182 Hope Street, Providence, RI 02912, USA

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ABSTRACT

We have identified radio and/or mid-infrared counterparts to 198 out of 350 sources detected at $\geq 5\sigma$ over $\sim 9$ deg$^2$ centered on the Chandra Deep Field South by the Balloon-borne Large Aperture Submillimeter Telescope (BLAST) at 250, 350, and 500 $\mu$m. We have matched 114 of these counterparts to optical sources with previously derived photometric redshifts and fitted spectral energy distributions to the BLAST fluxes and fluxes at 70 and 160 $\mu$m acquired with the Spitzer Space Telescope. In this way, we have constrained dust temperatures, total far-infrared/submillimeter luminosities, and star formation rates for each source. Our findings show that, on average, the BLAST sources lie at significantly lower redshifts and have significantly lower rest-frame dust temperatures compared to submillimeter sources detected in surveys conducted at 850 $\mu$m. We demonstrate that an apparent increase in dust temperature with redshift in our sample arises as a result of selection effects. Finally, we provide the full multiwavelength catalog of $\geq 5\sigma$ BLAST sources contained within the complete $\sim 9$ deg$^2$ survey area.

Key words: cosmology; observations – galaxies: high-redshift – infrared: galaxies – submillimeter – surveys

Online-only material: machine-readable tables

1. INTRODUCTION

Excluding the cosmic microwave background, approximately half of the extragalactic background radiation is emitted at far infrared (IR) and submillimeter wavelengths (e.g., Fixsen et al. 1998; Hauser & Dwek 2001) peaking around $\sim 200$ $\mu$m. However, relatively little is known about the sources responsible compared to the well explored optical universe where studies have enjoyed a head-start of several decades. Combining this with significant recent advances in submillimeter instrumentation, it is therefore not surprising that galaxy surveys are now turning to the submillimeter in the search for a more complete understanding of the formation of structure in the universe.

The first deep submillimeter surveys (e.g., Smail et al. 1997; Hughes et al. 1998; Barger et al. 1998) revealed a population of highly energetic dust obscured sources. Several clues suggested links between these systems and local ellipticals such as their similar volume densities (Scott et al. 2002; Dunne, Eales & Edmunds 2003) and clustering properties (e.g., Almaini et al. 2003; Blain et al. 2004) and their ability to rapidly form large stellar populations. Despite these early advances toward understanding the nature of the submillimeter population, the small areal coverage common to the early surveys yielded a low number of sources, resulting in the usual limitations due to small number statistics and sampling variance. This motivated the largest and last of the surveys conducted using the Submillimeter Common User Bolometer Array (SCUBA; Holland et al. 1999), the SCUBA HAIF Degree Extragalactic Survey (SHADES; Mortier et al. 2005). SHADES detected a total of $\sim 120$ sources (down to $\sim 3.5\sigma$) at 850 $\mu$m over an area of $\sim 700$ arcmin$^2$ (Coppin et al. 2006).

Although the large homogeneous sample of submillimeter sources detected by SHADES significantly enhanced previous samples, the survey still has three main deficits. (1) The areal coverage is small and therefore highly susceptible to sampling variance compared with optical surveys. (2) The SCUBA population appears to only represent a small fraction of the universe’s obscured star formation (see, for example, Chapman et al. 2005; Coppin et al. 2006; Dye et al. 2007). This is perhaps not surprising given that the energy of the far-IR/submillimeter background at 850 $\mu$m is $\sim 30$ times less than at $\sim 200$ $\mu$m where it peaks. (3) The SCUBA population seems to
reside almost exclusively at redshifts $z \gtrsim 1$, preventing proper investigation of the link between distant dusty galaxies and the local population.

This paper is concerned with a large new submillimeter survey centered on the Chandra Deep Field South (CDFS) recently carried out by the Balloon-borne Large Aperture Submillimeter Telescope (BLAST; Devlin et al. 2004; Pascale et al. 2008; Devlin et al. 2009). The survey covers $\sim 9$ deg$^2$ at each of the three BLAST wavelengths of 250, 350, and 500 $\mu$m. This is a leap of nearly 2 orders of magnitude in area compared with SHADES and energetically much nearer the peak of the far-IR/submillimeter background.

BLAST bridges the gap between the longest wavelength channels available to the Spitzer Space Telescope (Spitzer) at 24, 70, and 160 $\mu$m and SCUBA at 850 $\mu$m. As we show in this paper, BLAST is substantially more sensitive to galaxies at $z \lesssim 1$ where SCUBA found very few sources yet maintains an overlap with SCUBA’s sensitivity to moderate redshifts. For example, a 10 mJy 850 $\mu$m source at $z = 1$ with a dust temperature of 30 K has a typical flux of 80 mJy at 350 $\mu$m, well within the sensitivity levels reached by BLAST.

In order to derive scientific conclusions from the data in the same vein as for previous submillimeter surveys, the first step is to identify counterparts to the sources detected by BLAST. Like all single dish submillimeter observations made to date, the large beam size of BLAST precludes direct association with sources at optical to mid-IR wavelengths. A well proven procedure is to identify counterparts to submillimeter sources using radio interferometry. At radio wavelengths, submillimeter sources out to a redshift of $\sim 3$ can be readily detected. The typically low surface number density of radio detections results in a very low rate of chance alignments. In addition to radio counterparts, sources detected at 24 $\mu$m by Spitzer also prove useful for this purpose for the same reasons, albeit with typically lower positional accuracy (e.g., Ivison et al. 2007; Dye et al. 2008).

The main objective of this paper is to provide radio and 24 $\mu$m identifications of counterparts to the sources detected by BLAST in the CDFS. We have fitted spectral energy distributions (SEDs) to the three BLAST fluxes at 250, 350, and 500 $\mu$m and fluxes obtained by Spitzer at 70 and 160 $\mu$m. In this way, we have obtained best-fit rest-frame dust temperatures, bolometric luminosities, and star formation rates (SFRs). In Section 2 we describe the BLAST observations and the supporting multiwavelength data used in our analyses. Section 3 outlines our methodology, in particular the procedure used for identifying counterparts in the radio and at 24 $\mu$m. The results are presented in Section 4. Finally, Section 5 summarizes our findings and briefly discusses the implications of our results.

The multiwavelength catalog of $\gtrsim 5\sigma$ BLAST sources is given in Appendix C in Table 3 and contains 350 sources.

Throughout this work, we have assumed the following cosmology: $\Omega_m = 0.28$, $\Omega_\Lambda = 0.72$, $H_0 = 70$ km s$^{-1}$.

2. DATA

Figure 1 plots the geometry of the various data sets used in this paper. This section gives details of those data sets and a brief description of the BLAST data set itself. We refer the reader to Pascale et al. (2008) for a more detailed description of the primary characteristics of BLAST and Truch et al. (2008, 2009) for information on calibration and data reduction.

The 250, 350 and 500 $\mu$m observations analyzed in this paper were acquired during the BLAST 2006 flight launched on the 21st of December from McMurdo Station, Antarctica (BLAST06). The data encompass the CDFS and cover 8.7 deg$^2$ centered on $(3^h32^m, -28^\circ12')$ with mean $5\sigma$ sensitivities of 180, 150, and 100 mJy beam$^{-1}$ at 250, 350, and 500 $\mu$m, respectively. A region of 0.8 deg$^2$ centered on the southern field of the Great Observatories Origins Deep Survey (GOODS; Dickinson et al. 2003) at $(3^h32^m30^s, -27^\circ48')$. This deeper region, referred to hereafter as “BLAST GOODS South Deep” (BGS-Deep), reach mean $5\sigma$ sensitivities of 55, 45, and 30 mJy beam$^{-1}$ at 250, 350, and 500 $\mu$m, respectively (Devlin et al. 2009). The area surrounding BGS-Deep is referred to hereafter as BGS-Wide.

The BLAST time series data in each of the three bands were reduced using a custom-made pipeline (Pascale et al. 2008). Periodic observations of VY CMa conducted throughout the flight provide an absolute calibration for the telescope gain with uncertainties of 10%, 12%, and 13% at 250, 350, and 500 $\mu$m, respectively (although the calibration is highly correlated; see Truch et al. 2008). Signal and variance maps with $10' \times 10'$ pixels were generated using the maximum-likelihood mapping algorithm SANEPIC (Patanchon et al. 2008). In order to suppress residual large-scale noise, the SANEPIC maps were spatially filtered to whiten structure on scales larger than the telescope field of view (14$'$ x 7$'$). A catalog of point sources with a significance of $\geq 3\sigma$ for each band was compiled using a source-finding algorithm which selects the peaks in a smoothed map produced by the inverse variance weighted convolution of the image with the telescope point-spread function (PSF; Devlin et al. 2009).

The source lists were synthesized into a common catalog using a procedure which accounts for the significance and positional uncertainty of the counterparts in each band. The radius of the $1\sigma$ positional error circle, $\sigma_p$, for a submillimeter galaxy in a catalog with signal to noise $\mu$ which has not been
corrected for Eddington bias can be expressed as

\[
\sigma_p = 0.9 \theta (\mu^2 - (2\alpha + 4))^{-1/2}
\]  

for power-law counts of the form \(n(\gg f) \propto f^{-\alpha}\), where \(\theta\) is the full width at half maximum (FWHM) of the telescope beam (Ivison et al. 2007). The BLAST06 telescope beam is best fitted by Gaussians with a FWHM of 36 arcsec, 42 arcsec, and 60 arcsec at 250, 350, and 500 \(\mu m\), respectively (Pascale et al. 2008). Using this formula, error circles were calculated for each source in the individual catalogs assuming the slope of \(\alpha = 2.5\) measured by Devlin et al. (2009). A minimum 1\(\sigma\) error circle of 5\(\prime\) was imposed, equal to the 1\(\sigma\) pointing uncertainty of the maps.

The combined catalog is comprised of all sources with a significance \(\geq 5\sigma\) in at least one band. Sources from the other bands were considered counterparts if they were located within twice the radius of their respective error circles added in quadrature. Positions of sources in the resulting combined catalog were computed by averaging all the positions, weighted by \(\sigma_p^{-2}\).

The catalog contains 350 sources in total as listed\(^{15}\) in Table 3 in Appendix C. The number of sources detected at \(\geq 5\sigma\) by band is 178, 145, and 168 at 250, 350, and 500 \(\mu m\), respectively. 235 of the sources are located within BGS-Deep. Out of these, the sources detected at \(\geq 5\sigma\) by band is 121, 113, and 124 at 250, 350, and 500 \(\mu m\), respectively.

2.2. Radio Data

We have used two different catalogs for our radio counterparts. The first contains sources detected in the 1.4 GHz map observed by Miller et al. (2008) using the Very Large Array (VLA). The map covers an area of 0.33 deg\(^2\) centered on the GOODS region to an average rms sensitivity of \(\sim 8\) \(\mu Jy\) per 2\(\prime\)8 \(\times\) 1\(\prime\).6 beam. The published source catalog takes a very conservative detection threshold of \(7\sigma\). We therefore carried out our own source extraction on the map down to a lower detection threshold of 5\(\sigma\). This results in a larger source surface number density of \(\sim 0.7\) arcmin\(^{-2}\) compared to \(\sim 0.4\) arcmin\(^{-2}\) in the originally published catalog. Although this increases the risk of introducing spurious sources, our Monte Carlo method of associating counterparts to the BLAST sources takes this into account.

For the second radio catalog, we used the shallower but wider 1.4 GHz survey of (Norris et al. 2006) acquired using the Australia Telescope Compact Array. This survey covers a \(\sim 4\) deg\(^2\) area (2\(\prime\)2 \(\times\) 1\(\prime\)8) centered on (3\(\hbox{h}\)31\(\hbox{m}\), -28\hbox{\degree}06). The rms sensitivity of the survey is 40 \(\mu Jy\) per 5\(\prime\) beam giving rise to a source number density of 0.05 arcmin\(^{-2}\).

We carried out our identification of radio counterparts to the submillimeter sources separately on each catalog. When matching to sources in the wider Norris et al. catalog, we excluded the region covered by the deeper VLA data. We verified that all of the Norris et al. sources in this region were contained within the VLA data.

2.3. 24 \(\mu m\) Data

Similar to the radio data, our list of 24 \(\mu m\) Spitzer counterparts comprises two separate catalogs. The first is taken from Magnelli et al. (2009) as part of the Far-Infrared Deep Extragalactic Legacy Survey (FIDEL; Dickinson et al. 2007). The data cover 0.23 deg\(^2\) (30\hbox{\prime} \times 27\hbox{\prime}) centered on the GOODS region. The \(5\sigma\) point source sensitivity of FIDEL is \(\sim 30\) \(\mu Jy\) giving a surface number density of 12 arcmin\(^{-2}\).

The second 24 \(\mu m\) Spitzer catalog was taken from the Spitzer Wide-area InfraRed Extragalactic survey (SWIRE; Lonsdale et al. 2004) third data release.\(^{16}\) The 24 \(\mu m\) SWIRE data in the CDFS cover \(\sim 8\) deg\(^2\) (2\(\prime\)4 \(\times\) 3\(\prime\)4) centered on (3\(\hbox{h}\)32\(\hbox{m}\), -28\hbox{\degree}15'). The average 5\(\sigma\) point source sensitivity is \(\sim 100\) \(\mu Jy\) although only 24 \(\mu m\) sources detected at \(\geq 15\sigma\) are included in the catalog.

In the same manner as our identification of radio counterparts, we identified 24 \(\mu m\) sources separately for both 24 \(\mu m\) catalogs excluding the deeper FIDEL region when searching for SWIRE counterparts. We verified that all 24 \(\mu m\) SWIRE sources are contained within the FIDEL data.

2.4. 70 and 160 \(\mu m\) Spitzer Maps

In addition to the three BLAST fluxes, we also extracted flux from the SWIRE 70 and 160 \(\mu m\) Spitzer maps to improve constraints on our SED fitting. Both maps cover a rectangular area of \(\sim 2\hbox{\degree}3 \times 3\hbox{\degree}5\) centered on the 24 \(\mu m\) catalog (3\(\hbox{h}\)32\(\hbox{m}\), -28\hbox{\degree}15'). All bar five of the \(\geq 5\sigma\) BLAST sources with identified radio and/or 24 \(\mu m\) counterparts are located within these maps.

2.5. Photometric Redshifts

For the purpose of fitting SEDs to the BLAST and Spitzer photometry, we matched identified counterparts to optical sources with previously estimated photometric redshifts. We used the two main photometric redshift catalogs publicly available in CDFS.

1. The photometric redshift catalog of Wolf et al. (2004) from COMBO-17 (Classifying Objects by Medium-Band Observations in 17 filters) covers an area of 0.25 deg\(^2\) (0.5 \(\times\) 0.5) centered on GOODS. Redshifts are derived from optical photometry in five broad bands (\(U, B, V, R, I\)) and 12 interspersed medium bands. The surface number density of sources is 67 arcmin\(^{-2}\). Redshifts extend up to \(z \approx 2\) and have a median of \(\sim 0.9\).

2. The photometric redshift catalog of Rowan-Robinson et al. (2008) covers a total area of \(\sim 5\) deg\(^2\) (2\(\prime\)2 \(\times\) 2\(\prime\)3 but with gaps) centered on (3\(\hbox{h}\)32\(\hbox{m}\), -28\hbox{\degree}30'). The surface number density of sources is \(\sim 9\) arcmin\(^{-2}\). Redshifts are estimated from SWIRE photometry: the five broad optical bands \(u, g, r, i, \text{and}\ z\) and the two IRAC channels 3.6 and 4.5 \(\mu m\). The median redshift is \(\sim 0.9\) with 10% of galaxies at \(z > 2\) and 4% at \(z > 3\).

Table 1 lists the COMBO-17 and/or SWIRE photometric redshifts matched to the counterparts where available. Figure 5 shows the comparison for counterparts where both COMBO-17 and SWIRE redshifts exist.

3. METHODOLOGY

3.1. Identification Procedure

To identify radio and 24 \(\mu m\) counterparts, we applied the frequentist technique of Lilly et al. (1999) based on the method of Downes et al. (1986). The method searches for objects close to the submillimeter source and estimates the probability of each

\(^{15}\) The BLAST data used in this paper (including maps) are also available for download at http://blastexperiment.info.

\(^{16}\) See http://irsa.ipac.caltech.edu/data/SPITZER/SWIRE.
object being a chance alignment using a Monte Carlo approach. We applied the approach to the BLAST multiwavelength source list described in Section 2.1 in the following way.

1. Select a random position within the area common to the BLAST and radio catalogs.

2. Find the minimum of the quantity \( S = r_{\text{sep}}^2 n(> f) \) for each radio source within a separation cutoff of 20" of the random position (see below for justification of this cutoff). Here, \( r_{\text{sep}} \) is the radial separation between the radio source and the random position and \( n(> f) \) is the surface number density of radio sources brighter than the radio source.

3. Repeat steps (1) and (2) for \( N \) realizations to determine the distribution of the \( S \) for the radio sources.

4. Repeat steps (1)–(3) with the 24 \( \mu \)m catalog to determine the distribution of the \( S \) for the 24 \( \mu \)m sources.

The distribution of \( S \), \( D(S) \), then allows the probability \( P(< S_i) \) to be computed from a value \( S_i \) of a real potential counterpart \( i \):

\[
P(< S_i) = \frac{1}{N} \int_0^{S_i} D(S) dS. \tag{2}
\]

Note that, in general, up to a critical surface number density, \( \int_0^{\infty} D(S) dS < N \) since a certain fraction of the randomly chosen positions will not contain any radio (or 24 \( \mu \)m) sources within 20". Figure 2 shows the distributions obtained for radio and 24 \( \mu \)m counterparts in the FIDEL region.

The most likely counterpart is that with the lowest value of \( P \). Introducing a threshold in \( P \) gives a criterion for establishing BLAST sources without counterparts. In the analysis that follows later in this paper, we have only included counterparts with \( P \leq 0.05 \). Sources with radio and 24 \( \mu \)m counterparts were included if either or both counterparts satisfy \( P \leq 0.05 \). Although not included in any analysis, we have also listed counterparts in the area outside the FIDEL region with
the random positions that do not contain any radio
this does not constrain 5% of the open histogram. Computation of
additional false counterparts.
29 counterparts at the mere cost of including an expected two
on the basis that relaxing the threshold to 0.1 results in another
histograms indicates that a subset of the counterparts identified in the radio and at
not included in the histogram.)

0.05 < P < 0.1. As we discuss in Section 4.1, this is justified
on the basis that relaxing the threshold to 0.1 results in another
29 counterparts at the mere cost of including an expected two
additional false counterparts.

3.1.1. Determination of the Separation Cutoff

Selection of the separation cutoff depends on several factors. Clearly a smaller cutoff gives rise to fewer counterparts, increasing the likelihood of missing a true counterpart. Conversely, a larger cutoff increases the risk of associating a very bright but unrelated counterpart (i.e., S is small since n(> f) is small even though rsep is large). An added complication is that larger cutoffs increase the probability of overlapping positional error circles thereby complicating the matching process.

The separation cutoff should be a compromise between these factors. We have therefore selected our cutoff as the radius where

the expected number of excluded true counterparts is equal to the expected number of false counterparts. The procedure we used to determine this is as follows:

1. Using a large separation cutoff (e.g., 30”), perform an initial ID analysis as outlined above to compute values of P for all counterparts within the cutoff. Form the distribution of radial offsets of the primary counterparts (i.e., those counterparts with the lowest P per BLAST source).
2. Compute the number of expected false IDs by summing P over all primary counterparts. Repeat the ID analysis with decreasing values of the separation cutoff, computing the expected number of false IDs each time. This gives the false ID rate, i.e., the number of false IDs per interval separation as a function of the separation cutoff.
3. Subtract the false ID rate from the distribution of radial offsets determined in the first step. The result is the expected distribution of true counterparts which should have the form r e^{-r^2/2σ^2} (e.g., Ivison et al. 2007). Fit this to derive σ and hence determine the number of true counterparts that would be excluded as a function of separation cutoff.

Figure 3 shows the distribution of radial offsets of the primary radio counterparts within 30” of each BLAST source in the FIDEL region. The figure shows that the expected number of false counterparts is equal to the expected number of excluded true counterparts at a separation cutoff of 21”. Repeating this analysis for the 24 μm counterparts in the FIDEL region, we found an optimal separation cutoff of 19”. Similarly, the procedure returns optimal separation cutoffs of 28” and 26” for the radio and 24 μm counterparts in the region outside FIDEL, respectively. With this in mind, we chose a value of 20” as the separation cutoff for the FIDEL region and 25” for the region outside FIDEL. Whilst this is slightly conservative for the outer-FIDEL region, the fraction of real counterparts we would
expect to exclude is low. Similarly, although this cutoff is slightly larger than the optimal value for the 24 μm counterparts within the FIDEL region, the false ID rate is sufficiently low around 20″ to make a negligible increase in the number of expected false 24 μm counterparts. Section 4.1 quantifies the resulting expected number of false IDs for each counterpart catalog and region.

Note that the distribution of radial offsets in Figure 3 indicates that 68% of radio counterparts are within an offset of ~ 12″. The position error of a 5σ BLAST source detected at 250 μm from Equation (1) is ~ 8″. These values are consistent once positional uncertainties in the radio catalog and pointing errors on both the BLAST and radio catalogs are accounted for.

3.2. Matching to the Photometric Catalogs

Prior to matching to the photometric redshift catalogs, the identified radio counterparts were position-matched to the 24 μm counterparts. We used a separation tolerance of 3″ for this matching based on the 24 μm data PSF of FWHM ~ 6″ and the average radio data PSF of FWHM ~ 5″. In cases where a BLAST source has a radio and a 24 μm counterpart that both satisfy the selection criteria but are separated from each other by more than 3″, we selected the counterpart with the lowest value of P.

All identified BLAST source counterparts were then position-matched to the photometric redshift catalogs. For BLAST sources with a radio and a 24 μm counterpart, the average of the radio and 24 μm coordinates were used in the matching (since the radio and 24 μm PSFs are similar). We used the same positional tolerance of 3″ in matching up with the redshift catalogs. We found that in all cases where a counterpart is matched by both a COMBO-17 and SWIRE redshift (i.e., they are both within 3″ of the counterpart), the COMBO-17 and SWIRE sources are within 1″ of each other.

3.3. SED Fitting

We determined 250, 350, and 500 μm BLAST fluxes and the 70 and 160 μm Spitzer fluxes for the BLAST sources with identified photometric redshifts by reading off the flux in the beam-convolved maps at the position of the radio/24 μm counterpart. These fluxes were then fitted with a modified black body SED of the form

\[ S(\nu) = A(\nu)B(\nu, T) = \frac{A}{\nu^2} \exp\left(-\frac{h\nu}{kT}\right) \]

where the subscripts i and j span the three BLAST bands and the subscript k spans the 70 and 160 μm Spitzer bands. In this equation, \( \sigma_{ij}^{-1} \) is the inverse of the BLAST data covariance matrix, \( \sigma_k \) is the error on the kth Spitzer flux, \( f_i \) is the flux measured in the ith band, and \( f_j^m \) is the corresponding model flux computed by integrating the trial SED over the ith band response function. The total far-IR/submillimeter luminosities quoted in the results that follow were computed by integrating the best-fit SED over the wavelength range 10–2000 μm.

We have ignored the effects of flux boosting on the properties derived from the SED fits. In reality, since the BLAST differential source count density falls very rapidly with flux (approximately following \( dN/dS \propto S^{-3.5} \); see Patanchon et al. 2009), the effects of Eddington bias and source confusion mean that the fluxes in our source catalog are boosted. However, by restricting our analysis to a relatively bright subset of the BLAST source catalog and also extracting flux densities at the radio or MIPS source positions, we expect to reduce the effects of boosting. Repeating our analysis on a preliminary de-boosted set of fluxes made using a recipe adapted from Coppin et al. (2005) results in a bias toward higher temperatures and lower luminosities. The bias is within our error bars for sources in the wide field and larger for sources in the highly confused deep field. A full treatment of flux boosting in the BLAST data will be explored in future work.

4. RESULTS

Several of the results presented in this section, where stated, are limited to a robust sample of sources. We have defined this robust sample based on the results of the SED fitting discussed below. The robust sample is therefore a subset of those sources with photometric redshifts.

A source is considered robust if its best-fit rest-frame dust temperature is not at the extremes of our uniform temperature prior (i.e., if 10 K < T < 50 K) and its SED can be fitted with \( \chi^2 < N_{\text{dof}} + 2.71 \), where \( N_{\text{dof}} \) is the number of degrees of freedom of the fit. For normally distributed errors, this threshold in \( \chi^2 \) corresponds to excluding the worst fit 10% of SEDs. For almost all of our sources, \( N_{\text{dof}} = 3 \) since we have five flux measurements and two SED parameters (normalization and T). With these criteria, our robust sample contains 74 BLAST sources.

Defining the robust sample in terms of the SED fitting is motivated by the fact that source redshifts are fixed at the value of the photometric redshift estimated for the counterpart. If the assumed redshift is incorrect, either because the photometric redshift is intrinsically unreliable or because the BLAST source has been spuriously identified with the counterpart, then this will manifest itself either with a poor SED fit or by requiring an extreme temperature to obtain an acceptable fit.

4.1. Identifications

Table 1 lists the BLAST sources within the FIDEL region with identified radio and/or 24 μm counterparts. Table 2 lists the radio and 24 μm counterparts to the ≥ 5σ BLAST sources located outside the FIDEL region.

Within the FIDEL region the 24 μm identification rate (\( P \leq 0.05 \)) is 23/78 compared with the radio identification rate of the VLA data of 29/78. The overall identification rate, i.e., a BLAST source being identified with \( P \leq 0.05 \) by either a radio or 24 μm source is 39/78 in the FIDEL area. Splitting this by band, the overall rates (as a fraction of sources detected
at \( \geq 5\sigma \) at each wavelength) are 31/42 at 250 \( \mu m \), 26/45 at 350 \( \mu m \), and 16/48 at 500 \( \mu m \). In the area outside the FIDEL region, the 24 \( \mu m \) identification rate of the SWIRE data is 131/268 compared with the rate of the Norris et al. data (and the outer part of the VLA data) of 74/220.

Figure 6 plots the overall identification rate as a function of 250 and 500 \( \mu m \) flux for sources detected at \( \geq 5\sigma \) at each wavelength. The figure shows a small decline in the identification rate of BLAST sources toward fainter 250 \( \mu m \) fluxes and a stronger decline toward fainter 500 \( \mu m \) fluxes. Over the full area common to the radio and 24 \( \mu m \) data, this decline corresponds to 37 out of 150 of the 250 \( \mu m \) sources not being identified and 94 out of 146 of the 500 \( \mu m \) sources not being identified. Despite benefiting from a negative K-correction (which is quite weak at 250 \( \mu m \)), lower flux BLAST sources are more likely to reside at higher redshifts. The measured decrease in identification rate at lower fluxes therefore implies firstly that the unidentified sources lie at higher redshifts than the identified sources on average and secondly that there is a larger fraction of unidentified high redshift 500 \( \mu m \) sources. Section 4.2.1 discusses this further.

By summing the values of \( P \) determined in the identification process, the number of expected false counterparts in the sample can be estimated. Out of all 103 radio counterparts identified with \( P < 0.05, \sim 1 \) of these is expected to be false. Similarly, out of all 154 24 \( \mu m \) sources with \( P_{24} < 0.05, \sim 2 \) counterparts would be expected to be false. Limiting this to our robust sample of counterparts, the expected number of false identifications is \( \sim 1 \) out of 46 in the radio and \( \sim 1 \) out of 56 at 24 \( \mu m \).

Relaxing the threshold on \( P \) to 0.1 in the area outside the FIDEL region results in an additional 29 counterparts. Summing \( P \) over these 29 counterparts indicates that two of them would be expected to be chance alignments. On this basis, we have included counterparts up to \( P \leq 0.1 \) in Table 2. However, these additional sources are only listed in the table and are not included in any analysis in this paper.

### 4.2. Redshifts

Figure 4 shows the distribution of redshifts for our robust sample of 74 BLAST sources. The figure also shows the redshift distribution of the SCUBA sources detected at 850 \( \mu m \), at \( \geq 5\sigma \) at each wavelength) are 31/42 at 250 \( \mu m \), 26/45 at 350 \( \mu m \), and 16/48 at 500 \( \mu m \). In the area outside the FIDEL region, the 24 \( \mu m \) identification rate of the SWIRE data is 131/268 compared with the rate of the Norris et al. data (and the outer part of the VLA data) of 74/220.

Figure 6 plots the overall identification rate as a function of 250 and 500 \( \mu m \) flux for sources detected at \( \geq 5\sigma \) at each wavelength. The figure shows a small decline in the identification rate of BLAST sources toward fainter 250 \( \mu m \) fluxes and a stronger decline toward fainter 500 \( \mu m \) fluxes. Over the full area common to the radio and 24 \( \mu m \) data, this decline corresponds to 37 out of 150 of the 250 \( \mu m \) sources not being identified and 94 out of 146 of the 500 \( \mu m \) sources not being identified. Despite benefiting from a negative K-correction (which is quite weak at 250 \( \mu m \)), lower flux BLAST sources are more likely to reside at higher redshifts. The measured decrease in identification rate at lower fluxes therefore implies firstly that the unidentified sources lie at higher redshifts than the identified sources on average and secondly that there is a larger fraction of unidentified high redshift 500 \( \mu m \) sources. Section 4.2.1 discusses this further.

By summing the values of \( P \) determined in the identification process, the number of expected false counterparts in the sample can be estimated. Out of all 103 radio counterparts identified with \( P < 0.05, \sim 1 \) of these is expected to be false. Similarly, out of all 154 24 \( \mu m \) sources with \( P_{24} < 0.05, \sim 2 \) counterparts would be expected to be false. Limiting this to our robust sample of counterparts, the expected number of false identifications is \( \sim 1 \) out of 46 in the radio and \( \sim 1 \) out of 56 at 24 \( \mu m \).

Relaxing the threshold on \( P \) to 0.1 in the area outside the FIDEL region results in an additional 29 counterparts. Summing \( P \) over these 29 counterparts indicates that two of them would be expected to be chance alignments. On this basis, we have included counterparts up to \( P \leq 0.1 \) in Table 2. However, these additional sources are only listed in the table and are not included in any analysis in this paper.

#### 4.2. Redshifts

Figure 4 shows the distribution of redshifts for our robust sample of 74 BLAST sources. The figure also shows the redshift distribution of the SCUBA sources detected at 850 \( \mu m \).
by Chapman et al. (2005) and Aretxaga et al. (2007). The submillimeter sources in our robust sample are clearly located at significantly lower redshifts than those detected by SCUBA. The median redshift of the sample of 73 SCUBA sources of Chapman et al. (2005) lies at \( z = 2.2 \) with an inter-quartile range of 1.7–2.8 and the sample of 120 SCUBA sources of Aretxaga et al. (2007) has a median of \( z = 2.4 \) and inter-quartile range of 1.8–3.1. In comparison, the distribution of redshifts of our robust sample has a median of \( \sim 0.6 \) and an inter-quartile range of 0.2–1.0.

Figure 5 shows a comparison of the optical photometric redshifts for all sources that have a redshift provided by both Rowan-Robinson et al. (2008) and COMBO-17. The agreement is mediocre with a third of the 21 redshifts inconsistent at the \( > 3 \sigma \) level (although without uncertainties on the Rowan-Robinson redshifts the number of inconsistencies quoted here is an upper limit). However, in fitting the SEDs, for cases where both a Rowan-Robinson and COMBO-17 redshift exists, we took the redshift which gives the best SED fit to the observed submillimeter/far-IR data. Only three out of the 53 photometric redshifts are discrepant with the spectroscopic redshifts at the \( > 2 \sigma \) level.

We also very recently obtained spectroscopic redshifts for approximately half of our radio and/or 24 \( \mu m \) identified \( > 3 \sigma \) BLAST sources (Eales et al. 2009). Preliminary analysis has indicated excellent agreement with the photometric redshifts we have used in the current work. The inset panel in Figure 5 shows this comparison for the 53 sources in common and indicates that our method of selecting the photometric redshift that best fits the observed fluxes when two redshifts are available works well. Although we have not incorporated the spectroscopic redshifts in the analysis carried out in this paper, this excellent agreement increases the confidence in the source properties that follow from the SED fitting, since these strongly depend on the redshift assumed.

4.2.1. Comparison with Model Predictions

We have predicted the redshift distribution of the BLAST sources using an empirical model (Eales et al. 2009) derived from the results of the SCUBA Local Universe and Galaxy Survey (SLUGS; Dunne et al. 2000; Vlahakis et al. 2005). The model is based on the sample of 104 galaxies observed by Dunne et al. (2000) using SCUBA at 450 and 850 \( \mu m \). The galaxies form a statistically-complete sample above a 60 \( \mu m \) flux limit of 5.24 Jy and constitute the only large sample of galaxies with empirical spectral energy distributions that stretch from the far-IR to submillimeter wavebands, which is a major advantage over existing models for submillimeter surveys.

We can use the SLUGS sample to predict the source counts at any frequency in a straightforward way. The number of sources above a given 250 \( \mu m \) flux density is given by

\[
N(>f_{250}) = \sum_{j=1}^{104} \int_{0}^{z(z_j(z), f_{250})} \frac{1}{V_j} dV
\]

where \( V_j \) is the comoving volume in which the \( j \)th SLUGS source could have been detected in the original sample from which it was selected, and the integral is over comoving volume out to the redshift at which the source would be detected in the current sample. We assumed that the luminosity of the \( j \)th SLUGS galaxy is given by

\[
L_j(z) = E(z)L_j(0)
\]

where \( L_j(0) \) is the empirical luminosity of the \( j \)th SLUGS galaxy at the appropriate rest-frame wavelength and \( E(z) \) is an evolution function. We have implicitly assumed “luminosity evolution” rather than “number-density evolution,” which is necessary anyway because it is impossible to fit both the cosmic background radiation and the submillimeter source counts with number-density evolution. In practice, we have used the simple luminosity-evolution model from Rowan-Robinson
et al. (2001), in which luminosity is given by

$$L(t) = L(t_0) \left( \frac{t}{t_0} \right)^D \exp \left[ C \left( 1 - \frac{t}{t_0} \right) \right]$$  \hspace{1cm} (6)$$

where $t$ is the time from the big bang and $t_0$ is the time at the current epoch. $C$ and $D$ are parameters of the model. We have found that values of $C = 9$ and $D = 3$ give acceptable fits to the spectral shape and intensity of the cosmic background radiation and to the SCUBA 850 $\mu$m and Spitzer 70 $\mu$m source counts. By adjusting the integral limits in Equation (4), the distribution of redshifts can be computed.

The predicted redshift distribution for the BLAST galaxies detected at $\geq 5\sigma$ at 250 $\mu$m and at 500 $\mu$m using this approach is shown in the top panel of Figure 4. In addition, the figure shows the redshift distribution according to the galaxy evolution model of Lagache et al. (2004). The predictions apply specifically to the BLAST CDFS survey, taking into account the different areas and depths of BGS-Wide and BGS-Deep.

To allow for possible biases in our BLAST catalogue caused by flux boosting and source confusion, we have disregarded absolute model normalizations throughout this section and have instead normalized the model counts to match the BLAST counts. In this way, our aim is to compare only distribution morphologies. We refer the reader to Patanchon et al. (2009) for an account of the BLAST number counts and the consequent implications for models.

A more direct comparison of the model redshift distributions is shown in the bottom two panels of Figure 4. Here, we have limited the comparison to the FIDEL area where the BLAST, radio and 24 $\mu$m data are deepest and most uniform. The bottom left panel shows the redshift distribution of the 20 robust sources detected at 250 $\mu$m. Similarly, the bottom right panel shows the redshift distribution of the 11 robust sources detected at 500 $\mu$m. Both lower panels show the corresponding distributions predicted by our evolved SLUGS model and the Lagache et al. (2004) model.

The Lagache et al. (2004) and evolved SLUGS model distributions show considerable differences. In the 250 $\mu$m case, the largest discrepancy occurs at $z < 1$. The Lagache et al. model predicts a deficit around $z \approx 0.5$ at the division between the quiescent population at $z < 0.5$ and the starbursting population at $z > 0.5$. However, according to the evolved SLUGS model, a peak is anticipated at $z \approx 0.5$. The measured distribution more closely resembles the SLUGS model although the large uncertainty due to Poisson noise means that the data cannot be used to unambiguously validate one model over the other. In the case of the 500 $\mu$m sources, there are similar discrepancies between the models. Once again, the evolved SLUGS model appears more consistent with the observed redshifts but does not alter Poisson noise precludes verification of either model.

Despite their differences, neither of the model redshift distributions in Figure 4 implies that we have failed to identify counterparts or obtain redshifts for a significant number of $\geq 5\sigma$ sources beyond $z \approx 2$ where $> 80\%$ of the SCUBA population resides. Of the two models considered, the Lagache et al. model is most discrepant with our sample, implying that we may have missed a small fraction of higher redshift sources. This is indeed consistent with our expectations based on the declining identification rate of 250 $\mu$m sources toward fainter fluxes (see Figure 6). However, neither the Lagache et al. (2004) model nor the SCUBA model predicts a sufficient fraction of high redshift 500 $\mu$m sources required to explain the stronger decline in identification rate seen at fainter 500 $\mu$m fluxes.

![Figure 7. Correlation between 1.4 GHz radio flux and 24 $\mu$m Spitzer flux for all counterparts to the $\geq 5\sigma$ BLAST sources identified at both wavelengths. The filled symbols denote sources in the robust sample (all of which have photometric redshifts).](image-url)

A obvious question that arises is to what degree does the fraction of sources without redshifts reconcile the differences between the SCUBA redshift distributions mentioned previously and the redshift distribution of our robust sample? Would we expect some of these sources to coincide with the SCUBA population? Unfortunately, we can only provide an upper limit. Figure 7 plots the radio flux versus the 24 $\mu$m flux for all counterparts identified at both wavelengths. Sources in the robust sample (which all have photometric redshifts) are indicated by filled points. The distribution of non-robust sources (mostly without redshifts) is clearly not concentrated in any specific part of the $f_r$-$f_{24}$ plane, in particular at faint fluxes where more distant sources would be expected to lie. (Although not shown, the same is true when every source with a redshift is overplotted). The rate of assignment of redshifts within the subsample of BLAST sources with counterparts therefore does not decline at higher redshifts at a detectable level. This in turn means that if we had been able to obtain redshifts for all 198 identified counterparts, their redshift distribution would be similar in shape to that of our robust sample except with greater normalization. Therefore, even under the extreme assumption that all 153 unidentified sources lie at high redshift ($z \gtrsim 2$), there is still only an overlap of just under 50% with the SCUBA population.

However, we emphasize that the $\geq 5\sigma$ sources considered in this paper are at the bright end of the sources detected by BLAST within BGS-Deep/Wide. The fainter sources, generally detected with lower significance, are expected to probe higher redshifts. This does indeed seem to be borne out by the detection of a significant fraction of the extragalactic far-IR/submillimeter background from fainter, higher redshift BLAST sources (Pascale et al. 2009; Marsden et al. 2009).

### 4.3. Source SEDs

Tables 1 and 2 list the best-fit rest-frame dust temperatures and total far-IR/submillimeter luminosities for the 114 sources with available photometric redshifts. The SEDs for those sources located in the FIDEL region are plotted in Appendix A.

In Figure 8 we plot the total far-IR/submillimeter luminosity, $L_{\text{FIR}}$, of the BLAST sources in the robust sample against redshift. Superimposed on this plot are curves showing the minimum $L_{\text{FIR}}$ a source must have in order to be detected at $5\sigma$ in one of the
three BLAST bands. These thresholds were computed using the survey sensitivity in BGS-Deep (55, 45, and 30 mJy beam\(^{-1}\) at 250, 350, and 500 \(\mu\)m respectively to 5\(\sigma\)) hence sources in the shallower region will be subjected to a set of curves shifted to slightly lower redshifts. The band in which the detection limit occurs varies as a function of redshift and dust temperature (e.g., a 10 K source meeting the requirement for a detection of 5\(\sigma\) in one of the three bands will only ever be met in the 500 \(\mu\)m band). The figure shows that for a given \(L_{\text{FIR}}\) out to a redshift of \(z \approx 1.6\), cooler sources can be detected at greater distances. Beyond this redshift, 10 K sources begin to rapidly move out of the 500 \(\mu\)m band and increasingly warmer sources become more readily detected. However, since the curves for hotter sources (40–50 K) become flatter at higher redshifts, a small increase in temperature of a hotter source pushes the detection limit to much lower redshifts. The net result is that there exists a modal mid-range dust temperature that slowly rises with redshift.

A complication is that the above argument assumes that the sources have a uniform distribution of dust mass. In practice, a cooler source at high redshift must have substantially more dust than a hotter source to remain detected. Since sources with more dust are more rare, this greatly reduces the probability of detecting cooler sources (10–20 K) out to higher redshifts (\(z \gtrsim 1.5\)). We return to this point below.

Figure 9 shows the distribution of best-fit rest-frame dust temperatures in our robust sample for the assumed fixed value of \(\beta = 1.5\). The distribution is well approximated by a Gaussian of mean 26 K and 1\(\sigma\) width of 5 K. This spread in temperatures is comparable to the 1\(\sigma\) error on the mean of 4 K determined through error propagation. Fixing \(\beta = 2\) instead gives a similar distribution but shifted to slightly lower temperatures with a mean of 23 K.

Comparing our dust temperatures with those derived for submillimeter sources detected at 850 \(\mu\)m by SCUBA, we find that the BLAST sources are significantly cooler on average. The sample of 73 SCUBA sources of Chapman et al. (2005) has a median dust temperature of 36 ± 6 K; Kovacs et al. (2006) determined a median temperature of 35 ± 3 K for their sample of 15 sources, while the sample of 25 SHADES galaxies studied by Coppin et al. (2008) was found to have a median temperature of 29 K (but with a large scatter of 18 K). As we discussed in Section 4.2, the SCUBA sources lie at significantly higher redshifts on average, hence an obvious question is whether our sample of BLAST sources supports a trend for hotter sources at higher redshifts.

Figure 10 shows the rest-frame dust temperatures for the BLAST sources in our robust sample plotted against redshift. The scatter is large, but it is clear that hotter than average sources lie at higher redshifts. However, the selection effects discussed previously must be taken into consideration. The curves in Figure 10 are the sensitivity curves from Figure 8 transformed into the \(T-z\) plane. For a given redshift, the curves in Figure 10 show that there is a dust temperature where the threshold in luminosity for detection is minimized for a given redshift. Sources do not lie along this threshold because it corresponds to high dust masses which are rare.
corresponding to 

common at a given redshift, this minimum threshold luminosity is where a population of sources with a uniform distribution of temperatures and dust masses would be expected to lie. Moving to colder or hotter temperatures away from this threshold at a fixed redshift requires a higher luminosity for detection. This is one of two dominant selection effects.

The second dominant selection effect arises from the fact that in reality, the dust mass distribution is far from uniform. Moving toward colder temperatures along a line of constant luminosity in Figure 10 requires the dust mass of a source to increase rapidly to stay within the survey sensitivity limits. For example, moving from $T = 30 \text{ K}$ to $T = 20 \text{ K}$ along the curve corresponding to $L_{\text{FIR}} = 10^{12} \ L_\odot$ requires an increase in dust mass from $\sim 5 \times 10^6 \ M_\odot$ to $\sim 5 \times 10^7 \ M_\odot$ (assuming a dust mass opacity coefficient of 0.1 m$^2$ kg$^{-1}$). Using the dust mass function of local submillimeter galaxies determined by Vlahakis et al. (2005), there are $\sim 10$ times as many galaxies with a dust mass of $5 \times 10^6 \ M_\odot$ than with a dust mass of $5 \times 10^7 \ M_\odot$. This required dust mass at 20 K corresponds to the knee of the dust mass function, beyond which galaxies with more dust become vastly more rare. Repeating the estimate for 10 K results in an expected reduction in the number of galaxies by a factor of $\sim 10^6$. Along the higher luminosity sensitivity curves, the same principles apply but since dust mass is proportional to luminosity for a fixed temperature the knee of the dust mass function and therefore the sudden rarity of galaxies applies at warmer temperatures.

This strong selection effect pushes sources away from the minimum threshold luminosity plotted in Figure 10. The observed trend of increasing rest-frame dust temperature with redshift is therefore where the strength of both selection effects are approximately balanced. Both cause an observed increase in temperature with redshift, but the luminosity effect limits the upper detectable temperature and the dust mass effect limits the lower temperature.

In Figure 11, we plot the dust temperature of sources in our robust sample against luminosity. The straight line fit is $T = -12.9 + 3.4 \log_{10}(L_{\text{FIR}}/L_\odot)$. The increase in temperature at higher luminosity is a reflection of the trend discussed previously. This is consistent with a known positive correlation between intrinsic dust temperature and far-IR luminosity for luminous infrared galaxies in the local universe (Chapin et al. 2003; Chapin et al. 2009). A more complete investigation will be discussed in forthcoming work (E. L. Chapin et al. 2009, in preparation).

5. SUMMARY AND DISCUSSION

We have identified counterparts detected at 1.4 GHz and/or 24 $\mu$m to 198 of the 350 $\geq 5\sigma$ BLAST sources contained within the $\sim 9$ deg$^2$ of BGS-Wide and BGS-Deep centered on the CDFS. In the region within BGS-Deep covered by the deep 24 $\mu$m FIDEL catalog where we also have deep VLA data, the identification rate is 23/78 for the 24 $\mu$m sources and 29/78 for the radio sources. In the $\sim 8$ deg$^2$ surrounding the FIDEL region, the identification rate for 24 $\mu$m SWIRE sources is 131/268 compared with the rate of 74/220 using the Norris et al. radio catalog.

Of the identified counterparts, 114 have photometric redshifts previously estimated by COMBO-17 and/or Rowan-Robinson et al. (2008). Using these redshifts, we have fitted modified black body SEDs to the BLAST fluxes measured at wavelengths 250, 350, and 500 $\mu$m and Spitzer fluxes at 70 and 160 $\mu$m. We have defined a robust sample of 74 sources whose SEDs fit the observed fluxes with $\chi^2 \leq N_{\text{dof}}$ + 2.71 (rejecting the worse fit 10% assuming normal errors) and whose resulting best-fit dust temperatures are not at the extremes of 10 K or 50 K of our uniform temperature prior.

The distribution of redshifts of our robust sample has a median of $\sim 0.6$ and an inter-quartile range of 0.2–1.0. The dust temperatures are approximately normally distributed with a median temperature of $T \simeq 26 \pm 5 \text{ K}$ (for $\beta = 1.5$, or $T \simeq 23 \pm 5 \text{ K}$ for $\beta = 2$) and the distribution of bolometric far-IR/submillimeter luminosities has a median of $4 \times 10^{11} \ L_\odot$.

Comparing the $\geq 5\sigma$ submillimeter sources detected by BLAST with those detected by SCUBA at 850 $\mu$m, we find a stark contrast. It is clear from the redshift distributions alone that the BLAST sources in our robust sample are a significantly less distant population. The median redshift of submillimeter sources detected to date in 850 $\mu$m SCUBA surveys lies somewhere between $z = 2–2.5$ (e.g., Chapman et al. 2005; Aretxaga et al. 2007; Younger et al. 2007). In comparison, 75% of the robust BLAST sources, for which we have identified counterparts in a similar manner to the SCUBA surveys (i.e., with a combination of radio and 24 $\mu$m data, the same used by Ivison et al. 2007, for example), lie at $z < 1$.

This significant difference cannot be explained by our selection of robust sources. Within the subset of BLAST sources with identified counterparts, the robust sources form a uniform random sampling of the plane spanned by radio and 24 $\mu$m counterpart flux. In other words, we have not systematically failed to obtain redshifts for a more distant subset of identified BLAST sources where the radio and/or 24 $\mu$m flux would be expected to be lower on average. Therefore, we would not expect the redshift distribution of the full sample of 198 identified BLAST sources to extend to much greater redshifts. However, there remains the possibility that the remaining 153 BLAST sources without identified counterparts lie at higher redshifts on average. We have measured a decrease in the identification rate toward fainter BLAST fluxes which supports this hypothesis. Around a quarter of the 250 $\mu$m sources detected at $\geq 5\sigma$ remain unidentified compared to nearly two thirds of 500 $\mu$m sources.

We have compared our measured redshift distributions with predictions made by the galaxy evolution model of Lagache et al. (2004) and by our own model where we evolved the
local 850 \mu m luminosity function with the empirical models of Rowan-Robinson et al. (2001). Considering sources detected at 250 \mu m, our own model implies that we have not failed to identify a significant number of 250 \mu m sources at higher redshift within the survey sensitivity limits. However, the Lagache model predicts that we may have failed to identify a small fraction (~10%-15%) beyond \( z \gtrsim 2 \) which is compatible with our observed small decline in the identification rate at faint 250 \mu m fluxes. Conversely, at 500 \mu m, neither model implies a large enough fraction of high redshift sources to accommodate the strong decline in identification rate toward faint fluxes measured. This decline results in ~100 unidentified 500 \mu m sources. Even extending the models to include \( \geq 3\sigma \) sources only shows a ~25% increase in the number of sources predicted at \( z > 2 \).

Considering all of the evidence presented (and bearing in mind that the models are not absolutely normalized), the most likely explanation is that the unidentified BLAST sources do indeed lie at higher redshifts than the identified subset on average, but that they also include a significant fraction of lower redshift sources. Failure to identify a low redshift source will occur if the counterpart is too faint, either to the extent that it is not detected or that it yields a value of \( P \) in the ID procedure that falls outside the threshold. To conclude our discussion of redshifts, although we cannot fully quantify the overlap of the redshift distribution of BLAST sources considered in this paper with that of the SCUBA population, we can place a strong upper limit. Under the extreme assumption that all 153 unidentified sources lie at higher redshift (say \( z > 2 \)) than the 198 identified, the overlap with the SCUBA population is still just under 50%.

We have also found that the average dust temperature of the BLAST sources is clearly different to that of sources detected in the SCUBA surveys. The BLAST sources have a significantly cooler temperature distribution compared to the higher redshift 850 \mu m population. For example, Chapman et al. (2005) measured a median dust temperature of 36 ± 6 K. This is consistent with a trend observed in our sample of BLAST sources such that sources with higher dust temperatures are seen at higher redshifts. We have shown that this trend is the result of two strong selection effects.

This paper has addressed a small fraction of the analysis made possible by the multiwavelength catalog of BLAST sources published herein and the identification of their radio and 24 \mu m counterparts. Further analysis will be conducted in forthcoming BLAST papers.

An immediate priority is to increase the number of source redshifts. We have very recently obtained spectroscopic redshifts with the multi-fiber spectrometer, AAOmega, on the Anglo-Australian telescope for \( > 100 \) of the BLAST sources (Eales et al. 2009). Preliminary results show very close agreement with the subset of sources in common that have previously derived photometric redshifts, although the spectroscopic sample extends the total number significantly. The multiwavelength catalog (in combination with the Spitzer photometry at 70 and 160 \mu m) allows submillimeter photometric redshifts to be estimated for those sources without counterparts. With a larger sample of redshifts, more stringent limits can be placed on galaxy evolution models and the redshift distributions they predict. These redshifts also enable investigation of the evolution of the submillimeter luminosity function (E. L. Chapin et al. 2009, in preparation) and more rigorous investigation of the far-IR/radio correlation (Ivison et al. 2009, in preparation). Another possibility brought about by the spectra is measurement of equivalent line widths to provide a direct estimate of unobscured SFRs. Combining spectra with optical/near-IR morphology will give new insight into the types of systems that BLAST, and hence Herschel (see below), is sensitive to. Determination of the dominant processes at play will greatly assist our understanding of the link between these systems and the local population of galaxies.

The photometry upon which the submillimeter source properties derived in this paper have been based, the three BLAST bands at 250, 350, and 500 \mu m and the two Spitzer channels at 70 and 160 \mu m, is almost identical to what the Herschel Space Observatory is expected to deliver with SPIRE and PACS. Although the 9 deg\(^2\) BLAST survey analyzed here represents a significant leap forward in terms of areal coverage of submillimeter surveys, a subsequent leap is imminent with the anticipated several hundred square degree surveys to be conducted with Herschel.

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**Table 3**

The Multiwavelength Catalog of \( \geq 5\sigma \) BLAST Sources in BGS-Wide and BGS-Deep

| ID | BLAST ID | \( f_{250}/Jy \) | \( \sigma_{250}/Jy \) | \( f_{350}/Jy \) | \( \sigma_{350}/Jy \) | \( f_{500}/Jy \) | \( \sigma_{500}/Jy \) |
|---|---|---|---|---|---|---|---|
| 1 | BLAST J032921−280803 | 0.997 | 0.033 | 0.472 | 0.026 | 0.196 | 0.018 |
| 2 | BLAST J032956−284631 | 1.056 | 0.038 | 0.536 | 0.029 | 0.227 | 0.021 |
| 3 | BLAST J032741−282325 | 0.639 | 0.036 | 0.240 | 0.029 | 0.084 | 0.019 |
| 4 | BLAST J033235−275530 | 0.177 | 0.011 | 0.075 | 0.009 | 0.034 | 0.006 |
| 5 | BLAST J033131−272842 | 0.234 | 0.015 | 0.101 | 0.013 | 0.038 | 0.009 |
| 6 | BLAST J033229−274415 | 0.157 | 0.011 | 0.079 | 0.008 | 0.043 | 0.006 |
| 7 | BLAST J033250−273420 | 0.159 | 0.011 | 0.089 | 0.009 | \( \cdots \) | \( \cdots \) |
| 8 | BLAST J033548−274920 | 0.478 | 0.039 | 0.198 | 0.030 | 0.114 | 0.021 |
| 9 | BLAST J032916−273919 | 0.418 | 0.034 | 0.195 | 0.026 | 0.074 | 0.018 |
| 10 | BLAST J032850−263654 | 0.490 | 0.041 | 0.225 | 0.032 | 0.120 | 0.022 |

**Notes.** Reading from left to right, columns are: Internal ID as used throughout this paper, official combined BLAST source ID then flux and 1\( \sigma \) flux error for 250, 350, and 500 \mu m. To make the list, a source must be detected at \( \geq 5\sigma \) in at least one band. Note that the fluxes quoted here have not been de-boosted and that errors are purely instrumental, neglecting the effects of source confusion (see Section 3.3 for further discussion).

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Figure 12. Best-fit SEDs for $\geq 5\sigma$ BLAST sources in the FIDEL region. In the minimization, temperature is allowed to vary between 10 K and 50 K with a uniform prior, $\beta$ is fixed at the value 2.0. Redshifts are fixed at the redshift of the optical counterpart. Where more than one redshift exists, that which gives the best fit to the BLAST data is taken. The inset plot in each panel shows $\chi^2$ vs. $T$. 
Natural Sciences and Engineering Research Council (NSERC) of Canada. This work is based in part on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. S.D. is supported by the UK Science and Technology Facilities Council (STFC). We thank Guilane Lagache for advice on implementation of her galaxy evolution models.

Appendix A

Submillimeter SEDs

Figure 12 shows the best-fit SEDs to the BLAST and Spitzer 70 and 160 μm data for the $\geq 5\sigma$ BLAST sources in the FIDEL region.

Appendix B

Counterparts Outside the FIDEL Region

Table 2 lists the radio and/or 24 μm counterparts to the BLAST sources outside the FIDEL region.

Appendix C

Multimwavelength BLAST Catalog

Table 3 lists the 350 sources in the multimwavelength catalog of $\geq 5\sigma$ BLAST sources in BGS-Wide and BGS-Deep centered on the CDFS. See Section 2.1 for a description of how this catalog was created. All sources are detected with a significance of $\geq 5\sigma$ in at least one of the bands.

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