SEARCHING FOR THE HIGHEST REDSHIFT SOURCES IN 250–500 μm SUBMILLIMETER SURVEYS

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ABSTRACT

We explore a technique for identifying the highest redshift (z > 4) sources in Herschel/SPIRE and BLAST submillimeter surveys by localizing the position of the far-infrared dust peak. Just as Spitzer/IRAC was used to identify stellar “bump” sources, the far-IR peak is also a redshift indicator; although the latter also depends on the average dust temperature. We demonstrate the wide range of allowable redshifts for a reasonable range of dust temperatures and show that it is impossible to constraint the redshift of individual objects using solely the position of the far-IR peak. By fitting spectral energy distribution models to simulated Herschel/SPIRE photometry we show the utility of radio and/or far-infrared data in breaking this degeneracy. With prior knowledge of the dust temperature distribution it is possible to obtain statistical samples of high redshift submillimeter galaxy (SMG) candidates. We apply this technique to the BLAST survey of ECDFS to constrain the number of dusty galaxies at z > 4. We find 8 ± 2 galaxies with flux density ratios of S_{450} > S_{350}; this sets an upper limit of 17 ± 4 deg\(^{-2}\) if we assume all are at z > 4. This is <35 % of all 500 μm-selected galaxies down to S_{500} > 45 mJy (L_{IR} > 2 \times 10^{13} L_\odot) for z > 4. Modeling with conventional temperature and redshift distributions estimates the percentage of these 500 μm peak galaxies at z > 4 to be between 10% and 85%. Our results are consistent with other estimates of the number density of very high redshift SMGs and follow the decline in the star formation rate density at z > 4.

Key words: galaxies: evolution – galaxies: high-redshift – galaxies: starburst – infrared: galaxies – submillimeter: general – techniques: photometric

1. INTRODUCTION

The prevalence of dusty, infrared luminous galaxies at early times tests our theories about early galaxy formation and the production of metals. Semi-analytic models predict very small numbers of submillimeter galaxies (SMGs) at extreme redshifts (z > 4; e.g., Baugh et al. 2005), and the best observational constraints on the redshift distribution of SMGs are consistent with this (Chapman et al. 2005; Swinbank et al. 2008). Much attention has been paid to recent studies which have spectroscopically confirmed a small number of SMGs at z > 4 (Capak et al. 2008; Coppin et al. 2009; Daddi et al. 2009a, 2009b; Knudsen et al. 2010); however, these sources are still only a small fraction of the submillimeter population. Small number statistics and cosmic variance in current submillimeter surveys prohibit an accurate measure of the space density of the most distant SMGs.

The question of the prominence of the high-redshift tail of dusty SMGs can be addressed with imminent submillimeter wide area surveys such as those with the Herschel Space Observatory (Pilbratt 2001), the SCUBA-2 camera on the James Clerk Maxwell telescope (JCMT; Holland et al. 2006), and the AzTEC camera on the Large Millimeter Telescope (LMT; Wilson et al. 2008). The Herschel Space Observatory is currently collecting data from 70–500 μm over wide survey fields. With an aperture of 3.5 m, Herschel is only sensitive to ultra-luminous infrared galaxies (ULIRGs; L_{IR} > 10^{12} L_\odot) above z > 2 at 250–500 μm before it reaches the confusion limit. One advantage of SPIRE surveys is the simultaneous observations at three wavelengths 250, 350, and 500 μm, which samples the peak of the far-IR spectral energy distribution (SED) due to dust emission in high-redshift galaxies. With prior knowledge of the dust properties which describe the shape of the SED, the position of the far-IR peak is sensitive to the redshift of the galaxy.

In this Letter, we discuss the power and limitations of using the far-IR peak as a redshift indicator in submillimeter surveys. We apply this technique to the current BLAST survey of the Extended Chandra Deep Field South (ECDFS) and place an upper limit on the number density of 500 μm-selected SMGs at z > 4.

Throughout this Letter, we assume a standard cosmology with H_0 = 71 km s\(^{-1}\) Mpc\(^{-1}\), \Omega_M = 0.27, and \Omega_L = 0.73.

2. FAR-IR “BUMP” TECHNIQUE

The 1.6 μm bump in the near-infrared SED of galaxies arises due to a minimum in the H^+ opacity in the spectra of cool stars. This bump has been used in extragalactic Spitzer/IRAC surveys to identify sources in a specific redshift range (e.g., Wright et al. 1994; Sawicki 2002; Farrah et al. 2008). A similar, but factor of ~2–3 broader, peak exists in the SED of galaxies at far-IR wavelengths which is caused by the integrated thermal emission from dust of different temperatures. This SED is often parameterized as a blackbody distribution of a particular far-infrared color temperature (T_{dust}) with an additional term to account for the dust emissivity\(^4\) (e.g., Blain et al. 2002).

The challenge with using the far-IR bump as a redshift indicator is that the average dust temperature and the redshift are degenerate (e.g., Blain 1999; Blain et al. 2003). Wien's displacement law tells us that the wavelength of the peak of a blackbody scales with the dust temperature. Coupling this with the displacement of the peak due to redshift we find that the observed wavelength of the far-IR peak depends linearly on both the redshift and the inverse of the dust temperature:

\[ \frac{\lambda_{\text{obs}}}{\lambda_{\text{max}}} = \frac{(1 + z)}{T_{\text{dust}}}. \]

\(^4\) In this Letter, we assume a dust emissivity, β = 1.5. The choice of emissivity affects the derived color temperature.

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The most luminous galaxies in the local universe show far-infrared color temperatures that peak at \( \sim 40 \) K, although there is a significant scatter in luminosity-temperature parameter space (e.g., Dunne et al. 2000). For a reasonable range of dust temperatures for ULIRGs, sources that peak at 500 \( \mu \)m can be found anywhere between \( z \sim 3-6 \). This is a very large range in redshift, and without prior information about the dust temperature it is difficult to further constrain the redshift with the SPIRE data alone.

### 3. HIGH-REDSHIFT CANDIDATES IN THE ECDFS BLAST SURVEY

In order to test this technique on observations, we use the data from the BLAST survey of ECDFS (Devlin et al. 2009). BLAST has the same three detectors as Herschel/SPIRE but with beam sizes that are twice as big: 36, 42, 60 arcsec FWHM at 250, 350, and 500 \( \mu \)m, respectively (Marsden et al. 2009). We use the publicly released BLAST maps\(^5\) and the matched filter catalogs (Chapin et al. 2010). These matched filter catalogs do a much better job at de-blending adjacent sources and result in higher signal-to-noise ratios than previous BLAST catalogs (see Chapin et al. 2010 for further details). We restrict our analysis to the central 0.47 deg\(^2\) of the BLAST image where \( \sigma_{\text{inst}} < 10 \) mJy at 500 \( \mu \)m. We have conservatively added the confusion noise in quadrature with the instrument noise (\( \sigma_{\text{conf}}^2 + \sigma_{\text{inst}}^2 = \sigma_{\text{tot}}^2 \)) for all analysis in this Letter. We only consider detections if they are \( >5\sigma_{\text{tot}} \) (\( >3\sigma_{\text{tot}} \)). In this central region, there are 23 galaxies robustly detected at 500 \( \mu \)m with \( S_{500} > 45 \) mJy. We match the 500 \( \mu \)m-selected galaxies to the matched filter catalogs at 250 \( \mu \)m and 350 \( \mu \)m; we consider any \( >5\sigma_{\text{inst}} \) detection within a radius of 60 arcsec to be the counterpart to the 500 \( \mu \)m emission. For sources which are undetected at these other wavelengths, we set upper limits on the 350 and 250 \( \mu \)m fluxes from the 90\% completeness limits of the survey (Chapin et al. 2010) which is equivalent to \( 3\sigma_{\text{det}} \).

Of these 23 500 \( \mu \)m-selected galaxies, 8 have \( S_{500} > S_{350} \) indicating that the dust SED peaks at or near 500 \( \mu \)m—we refer to these galaxies as 500 \( \mu \)m “peakers” (although their peak may be at even longer wavelengths). Interestingly, none of these 500 \( \mu \)m peakers (detected at \( >5\sigma_{\text{inst}} \)) are detected above \( 5\sigma_{\text{inst}} \) at 250 and 350 \( \mu \)m. We inspected all of these candidates by hand in the BLAST images to make sure they are not obviously blended.

| ID                        | \( S_{500} \) (mJy) | \( S_{350} \) (mJy) | \( S_{250} \) (mJy) | Field |
|---------------------------|----------------------|----------------------|----------------------|-------|
| BLASTJ033311-275611       | 56 ± 14              | <45                   | <60                  | E     |
| BLASTJ033312-275548       | 53 ± 14              | <45                   | <60                  | E     |
| BLASTJ033215-275030       | 50 ± 14              | <45                   | <60                  | E     |
| BLASTJ033254-273303       | 50 ± 14              | <45                   | <60                  | E     |
| BLASTJ0334-274217         | 50 ± 14              | <45                   | <60                  | E     |
| BLASTJ033256-280105       | 48 ± 14              | <45                   | <60                  | E     |
| BLASTJ033159-273515       | 47 ± 14              | <45                   | <60                  | E     |
| BLASTJ033317-274926       | 46 ± 14              | <45                   | <60                  | E     |

Notes. IDs and fluxes come from Chapin et al. (2010); the uncertainties listed here include both instrument and confusion noise (\( \sigma_{\text{tot}} \)). The confusion noise is assumed to be 12, 13, and 15 mJy at 500, 350, and 250 \( \mu \)m, respectively (Chapin et al. 2010). Upper limits correspond to the flux where the catalogs are 90\% complete which is equivalent to roughly \( 3\sigma_{\text{tot}} \). The Field column indicates if the source is within the ECDFS (E) and/or the GOODS-S (G) areas.

We have not attempted to correct for flux boosting (e.g., Coppin et al. 2006) in this analysis but, since we are not interested in the absolute fluxes and only the relative colors, this is less of a concern. In addition, by considering only higher signal-to-noise ratio sources we ensure that this effect is minimal. In order to assess how photometric uncertainties (from both confusion and instrument noise) affect the number of 500 \( \mu \)m peaks, we ran a Monte Carlo simulation to randomly sample the fluxes of each of the 23 sources from a Gaussian distribution \( \pm \sigma_{\text{tot}} \). We find that photometric uncertainties can vary the number of sources with \( S_{500} > S_{350} \) by 2. Thus our final number of 500 \( \mu \)m peakers is 8 ± 2.

These eight high-redshift candidates are listed in Table 1 along with their fluxes, and Figure 1 shows an example SED for one source. Five of these 500 \( \mu \)m peakers are within the ECDFS field and one is within the smaller GOODS-S region (see Table 1). The source within GOODS-S is associated (6 arcsec away) with an AzTEC 1.1 mm detected source (GS11; Scott et al. 2010); however, flux boosting in the BLAST bands prohibits a detailed comparison.

Knowing that a source peaks at (or near) 500 \( \mu \)m does not provide a definitive redshift due to the degeneracy between redshift and temperature (e.g., Figure 2). If we conservatively assume that all 500 \( \mu \)m peakers are at \( z > 4 \), we can obtain an upper limit on the number density of \( z > 4 \) galaxies predicted in Herschel SPIRE surveys. Based on our analysis of the BLAST data, the number density of galaxies (with \( S_{500} > 45 \) mJy) which peak at 500 \( \mu \)m is 17 ± 4 deg\(^{-2}\). We expect that some of these 500 \( \mu \)m peakers will be at \( z < 4 \) since Figure 2 shows that sources cooler than 40 K can have \( S_{500} > S_{350} \) but be at \( z < 4 \).

To get an estimate of the contamination of low-redshift, cooler galaxies in the 500 \( \mu \)m peaker sample, we must assume a redshift and dust temperature distribution. Assuming a flat redshift distribution\(^6\) and a dust color temperature distribution of 35 ± 7 K,\(^7\) we estimate that 15% of 500 \( \mu \)m peakers will be...
$z < 4$ (left panel of Figure 2). In addition, we must also account for the contribution from warmer sources at $z > 4$ but which peak at lower wavelengths ($S_{500} < S_{350}$). Assuming a sample of sources at $z > 4$ again following a dust temperature distribution of $35 \pm 7$ K, we find that only 10% have $S_{500} < S_{350}$. These two factors roughly cancel each other, and we are left with a constraint on the number density of $z > 4$ sources (with $S_{500} > 45$ mJy) of $< 17$ deg$^{-2}$.

The above limit on the number density of $z > 4$ SMGs ambitiously assumes a flat redshift distribution. If instead we assume the observed redshift distribution of SMGs ($2.2 \pm 0.8$; Chapman et al. 2005; Pope et al. 2006), we find only 10% of the 500 $\mu$m peakers at $z > 4$ (right panel of Figure 2) which brings the number density estimate down to 2 deg$^{-2}$. Based on our analysis of the BLAST data, we conclude that the number density of $S_{500} > 45$ mJy sources at $z > 4$ is $< 17$ deg$^{-2}$ and could be as low as 2 deg$^{-2}$.

With some assumptions about the dust temperature distribution, we have shown that the submillimeter color selection, $S_{500} > S_{350}$, is a plausible way to identify samples containing the highest redshift SMGs selected at these wavelengths (although these samples contain contamination from lower redshift objects). Without further multi-wavelength data, it is impossible to tell individually which of the eight candidates are at $z > 4$ and which are just peaking at 500 $\mu$m because they have cooler dust temperatures. One way to test the reality of these high-redshift candidates is to further constrain their SEDs with data at longer submillimeter wavelengths such as those from the 870 $\mu$m LABOCA survey of ECDFS (Weiß et al. 2009). In order to make a robust comparison between the LABOCA and BLAST fluxes, a correction for flux boosting needs to be applied to both surveys using the same method (e.g., Coppin et al. 2006). This is beyond the scope of this Letter but should be possible with full access to the signal and noise maps from both surveys. Another potential way to break the degeneracy between redshift and temperature for these candidates is with the radio and/or far-IR (e.g., 100 $\mu$m) flux; we discuss this further in the next section.

4. USING RADIO AND FAR-IR DATA TO BREAK THE $z$–$T$ DEGENERACY

Photometry from 250–500 $\mu$m alone can provide an accurate measure of $(1 + z)/T_{dust}$. Figure 3 shows a simulation of Herschel SPIRE photometry for a source that peaks at 500 $\mu$m. Fitting modified blackbody models to this data we find the pairs of $T$ and $z$ that fit these data (panel (b) of Figure 3) and the resulting $L_{FIR}$ (panel (c) of Figure 3).

The radio emission from galaxies is known to correlate well with the infrared emission in the local universe (Condon 1992). Because of this radio-infrared correlation, radio data are often used to help identify counterparts to SMGs (e.g., Ivison et al. 2002) and to constrain the redshift (e.g., Carilli & Yun 1999; Hughes et al. 2002; Aretxaga et al. 2007). We demonstrate the latter point in panel (d) of Figure 3. Here, we assume the average value and scatter in the $q$ parameter from fitting local galaxies (Yun et al. 2001). The radio flux is not degenerate with the redshift; however, unfortunately, the large scatter in the local radio–IR correlation provides fairly loose constraints on the redshift of individual objects from the radio flux. Nevertheless, a large fraction of the bright SMGs detected with SPIRE will be above the flux limits of deep ($\sigma_{\text{radio}} < 5$ mJy) 1.4 GHz radio surveys. With large statistical samples, the redshift distribution inferred from including radio observations should be robust, assuming the radio–IR correlation holds out to high redshift.

Below $\sim 50$ $\mu$m rest frame, the SED of galaxies is no longer dominated by the single temperature-modified blackbody but instead by warmer dust components. This can be seen in panel (a) of Figure 3 where the dash-dotted curve is a Chary & Elbaz (2001, CE01) template representative of local star-forming galaxies. Fitting the CE01 templates (allowing the luminosity and temperature to vary) to the simulated SPIRE photometry...
we estimate the 100 $\mu$m flux as a function of redshift (panel (e) of Figure 3). While the curve is not smooth (due to discrete templates within the CE01 library), overall the far-IR flux can constrain the redshift for this simulated galaxy with no prior assumption on its dust temperature. The dotted line in panel (e) of Figure 3 shows the sensitivity of the deepest Herschel PACS extragalactic survey (GOODS Herschel, PI: D. Elbaz); this deep survey should detect bright SMGs beyond $z \sim 3$ by measuring the redshifted emission from warm dust that is heated in O&B star-forming regions and appears to correlate well with ongoing star formation (Calzetti et al. 2005).

5. DISCUSSION

From the BLAST ECDFS data we estimate a space density of $<17$ deg$^{-2}$ for sources with $S_{850} > 45$ mJy at $z > 4$; this is $<35$% (8/23) of all sources selected down to these depths in the BLAST data. These bright 500 $\mu$m-selected SMGs at $z > 4$ contribute $<1$% of the total background emission at 500 $\mu$m (Fixsen et al. 1998).

Constrained by a recent analysis of the infrared extragalactic background light (EBL), galaxies evolution models predict the source density of galaxies with $S_{850} > 27$ mJy$^6$ at $z > 4$ to be 1–5 deg$^{-2}$ (Chary & Pope 2010). The range of predicted number density comes from considering two evolutions of the models both of which fit the observed EBL. We find that our current observational constraint is consistent with both evolutionary scenarios. Future submillimeter surveys with much larger telescopes such as JCMT, LMT, and CCAT will reach much deeper flux limits before hitting the confusion limit. With these surveys, we can expect to detect many more dusty galaxies at $z > 4$; the models in Chary & Pope (2010) predict a number density of 40–200 deg$^{-2}$ at $z > 4$ for galaxies down to 5 mJy at 500 $\mu$m.

In the past two years, the tally of $z > 4$ spectroscopically confirmed SMGs has grown from zero to five$^9$ (Capak et al. 2008; Coppin et al. 2009; Daddi et al. 2009a, 2009b). Coppin et al. (2009) estimate the number density of SMGs at $z > 4$ by combining these five sources from three independent submillimeter surveys and find a lower limit of $>7$ deg$^{-2}$. While this is consistent with our predictions for 500 $\mu$m-selected galaxies, we note that the sensitivities of the BLAST and submillimeter surveys are not the same at $z = 4$; only 1/5 of the $z > 4$ spectroscopically confirmed SMGs might be detected down to the BLAST ECDFS survey depths (assuming a typical SMG dust temperature). Folding this in the Coppin et al. (2009) estimate down to $S_{850} > 20$ mJy scales to $>1.4$ deg$^{-2}$ at $z > 4$.

There is some evidence that large numbers of very massive galaxies at $z > 4$ pose a substantial challenge to standard galaxy

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$^6$ In order to compare to the models, we need to assume a rough correction for flux boosting of the BLAST measurements. Based on Eales et al. (2009), we adopt an average correction of 0.6 to the BLAST fluxes which effectively brings the flux limit down to 27 mJy.

$^9$ A sixth $z > 4$ SMG recently appeared in the literature (Knudsen et al. 2010).
We present eight candidate 500 μm “peakers” from the BLAST ECDFS survey with $S_{500} > 45$ mJy; a fraction of which we expect to be at $z > 4$ depending on the distribution of dust temperatures. The number density of these high-redshift candidates is $<17$ deg$^{-2}$ and is consistent with the number densities of the brightest 850 μm-selected galaxies. The corresponding fraction of 500 μm-selected galaxies in the BLAST survey which could be at $z > 4$ is $<35\%$.

To further constrain the space density of the most distant SMGs will require deep, wide area surveys with Herschel/Spire in addition to sufficiently deep multi-wavelength data to weed out the genuine high-redshift candidates from 500 μm “peakers” that are lower redshift galaxies with cooler than average dust temperatures. Regardless, our upper limits on the number density of $z > 4$ luminous dusty galaxies suggest a strong decline in their number density from $z \sim 2$.

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