New Observational Constraints and Modeling of the Infrared Background: Dust Obscured Star-Formation at z > 1 and Dust in the Outer Solar System

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ABSTRACT

We provide measurements of the integrated galaxy light at 70, 160, 250, 350 and 500\,µm using deep far-infrared and submillimeter data from space (\textit{Spitzer}) and balloon platform (BLAST) extragalactic surveys. We use the technique of stacking at the positions of 24\,µm sources, to supplement the fraction of the integrated galaxy light that is directly resolved through direct detections. We demonstrate that the integrated galaxy light even through stacking, falls short by factors of 2−3 in resolving the extragalactic far-infrared background. We also show that previous estimates of the integrated galaxy light (IGL) through stacking, have been biased towards high values. This is primarily due to multiple counting of the far-infrared/submillimeter flux from 24\,µm sources which are clustered within the large point spread function of a brighter far-infrared source. Using models for the evolution of the luminosity function at z < 1.2 which are constrained by observations at 24\,µm and 70\,µm, and which are consistent with the results from the stacking analysis, we find that galaxies at z < 1.2, account for \sim 95−55\% of the extragalactic far-infrared background in the \sim 70−500\,µm range respectively. This places strong upper limits on the fraction of dust obscured star-formation at z > 1, which are remarkably, below the values derived from the extinction corrected ultraviolet luminosities of galaxies. The largest fraction of the total 40−500\,µm EBL comes from galaxies between L_{\text{IR}}=L(8−1000\,µm)=10^{10−11.5}\,L_\odot; ultraluminous infrared galaxies with L_{\text{IR}} > 10^{12}\,L_\odot contribute only 5\%. We use the results to make predictions for the nature of galaxies that extragalactic surveys with \textit{Herschel Space Observatory} will reveal. Finally, from our constraints
on the far-infrared IGL, we provide evidence for the existence of ice mantle dust, orbiting the sun at a distance of \( \sim 40 \) AU, which is contributing intensity to both the near- and far-infrared background. The presence of this component which is a tiny fraction of the zodiacal light emission even at high ecliptic latitudes, eliminates any discrepancy between the integrated galaxy light and the diffuse, extragalactic background light at all infrared wavelengths.

Subject headings: cosmology: observations — diffuse radiation — galaxies: evolution — galaxies: high-redshift — Kuiper Belt

1. Introduction

The extragalactic background light (EBL)\(^1\) at far-infrared (FIR) wavelengths, spanning a wavelength range of \( 40 - 1000 \) \( \mu \)m, is the sum total of radiation from all astrophysical processes over cosmic time that is absorbed by dust and re-radiated. It places a strong constraint on the fraction of nucleosynthesis and accretion activity that is obscured by dust. Decomposition of the EBL into the contribution from individual galaxies as a function of redshift, provides a more complete understanding of the rate of build up of stellar mass and the growth of black holes over cosmic time and thereby helps identify the epoch at which most of the stars and black holes in the present day Universe formed.

The FIR EBL is thought to have a total intensity between \( 40 - 1000 \) \( \mu \)m of \( \sim 25 \) nW m\(^{-2}\) sr\(^{-1}\) although values as high as \( \sim 55 \) nW m\(^{-2}\) sr\(^{-1}\) have been suggested by DIRBE observations (Hauser et al. 1998; Finkbeiner et al. 2000). Much of the difference arises due to the difficulty in subtracting the contribution from zodiacal light emission. The zodiacal light contributes \( \sim 30\% \) of the line of sight intensity at \( 140 \mu \)m in even a relatively high ecliptic latitude (\( \beta \sim 45^\circ \)) field like the Lockman Hole, with a rapidly increasing fractional contribution at shorter wavelengths (Hauser et al. 1998). Even small errors in the subtraction of the zodiacal light propagate through as large errors in the estimate of the FIR EBL, an issue which has plagued measurements of the EBL at \( 60 \mu \)m and \( 100 \mu \)m.

Despite the fact that it is measured with a factor of \( \sim 100 \) less precision than the cosmic microwave background, the FIR EBL is arguably the second most energetic extragalactic background after the cosmic microwave background which has a total intensity of \( \sim 1000 \) nW m\(^{-2}\) sr\(^{-1}\). The intensity of the FIR EBL is comparable, if not in excess of the intensity of the optical/near-infrared extragalactic background, whose measurement is

\(^1\)Also referred to as the Cosmic Infrared Background
affected by similar uncertainties associated with the zodiacal light contribution (Bernstein 2007; Levenson et al. 2007). Since the optical/near-infrared EBL measures the redshifted contribution of unobscured starlight and AGN activity, integrated over cosmic time, the fact that the two intensities are comparable, illustrates the importance of dust obscuration in quantifying the bolometric luminosity of star-forming galaxies and active galactic nuclei.

Ever since the direct measurement of the EBL using the Far-Infrared Absolute Spectrometer (FIRAS) and the Diffuse Infrared Background Experiment (DIRBE; Puget et al. 1996; Hauser et al. 1998; Fixsen et al. 1998), various attempts have been made to identify the individual sources contributing to the background. The sum of the contribution of individual galaxies is termed the integrated galaxy light (IGL). Using backward evolution models which fit multiwavelength number counts, Chary & Elbaz (2001, hereafter CE01) demonstrated that dust obscured infrared luminous galaxies contribute 85% of the 140 $\mu$m EBL and that 82% of the peak of the FIR EBL arises from galaxies at $z < 1.5$. The 140 $\mu$m EBL is $\sim$60% of the total FIR EBL in the CE01 models. This implies that about 50% of the total FIR EBL arises at $z < 1.5$.

Elbaz et al. (2002) utilized model spectral energy distributions to estimate the contribution to the FIR EBL of infrared luminous galaxies individually detected by the ISOCAM in a deep 15 $\mu$m survey in the Hubble Deep Field-North. They found that the ISOCAM LIRGs at $z < 1$ contribute 16$\pm$5 nW m$^{-2}$sr$^{-1}$ of the 140 $\mu$m background. More recently, by stacking the far-infrared data, Bethermin et al. (2010) showed that galaxies with 24 $\mu$m flux densities $>35$ $\mu$Jy contribute 9.0$\pm$1.1 nW m$^{-2}$sr$^{-1}$ of the 160 $\mu$m background. Based on photometric redshifts, these galaxies are primarily thought to be infrared luminous galaxies at $z \sim 1$ with a tail extending to $\sim 2.5$ (Caputi et al. 2007).

In this context, the recent results from Balloon Large Aperture Submillimeter Telescope (BLAST) have been somewhat surprising (Devlin et al. 2009; Marsden et al. 2009). Using a technique similar to Dole et al. (2006), the BLAST team estimated that stacking on sources with 24 $\mu$m flux density greater than 13 $\mu$Jy results in an IGL of 8.6$\pm$0.6 nW m$^{-2}$sr$^{-1}$ at 250 $\mu$m (i.e. the majority of the EBL at this wavelength). Furthermore, the conclusion is that 24 $\mu$m detected galaxies contribute $\sim$80-90% of the total FIR EBL between 250 and 500 $\mu$m. The deep 24 $\mu$m data which have been used for their analysis are only sensitive to galaxies brighter than $10^{10}$ L$_{\odot}$ at $z \sim 1$ and $>10^{11}$ L$_{\odot}$ at $z \sim 2$ (Chary 2007a). It is well known that there is a whole population of Lyman-break galaxies which are less luminous and which appear to have significant dust obscuration based on their UV-slope. Although they should be contributing to the EBL, the BLAST analysis seems to suggest that the contribution from fainter galaxies is surprisingly small.

In this paper, we utilize deep, public Spitzer data taken as part of the Far-Infrared
Deep Extragalactic Legacy (FIDEL; P.I. M. Dickinson) survey\textsuperscript{2} at 70 and 160 µm and the publicly released BLAST maps at 250, 350 and 500 µm to evaluate the consistency of these different estimates. We combine direct detections of sources with stacking analysis to provide lower limits to the integrated galaxy light. We utilize recent measurements of the far-infrared luminosity function out to \(z \sim 1.3\), in conjunction with the model spectral energy distribution of galaxies based on various spectroscopic and imaging data, to determine the nature of sources contributing to the far-infrared background as a function of redshift and luminosity. We place constraints on dust obscured star-formation at \(z > 1\) and discuss implications for deep Herschel extragalactic surveys. Finally, we propose the existence of a previously unknown cloud of high albedo dust grains orbiting the Sun at a distance of \(\sim 40\) AU which contributes significantly to the intensity of the near- and far-infrared background.

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

### 2. The Integrated Galaxy Light from Direct Detections and Stacking

The integrated galaxy light is the sum of the observed light from individually detected galaxies at a particular wavelength. Due to the sensitivity limit of a survey, it is difficult to directly detect the dominant population of galaxies contributing at a particular wavelength. This is particularly difficult at far-infrared wavelengths, since the sensitivity of far-infrared detectors are relatively poor compared to those at shorter wavelengths. Furthermore, due to the large point spread function, source confusion dominates the limiting flux of a survey.

It is possible to assess the total intensity contribution from galaxies below the detection limit of a survey using the technique of stacking. This requires knowing the positions of the galaxies in the survey area from a deeper, less confused survey. The 24 µm observations of the FIDEL fields with Spitzer provide a particularly useful sample of galaxies. The surveys at this wavelength are \(\gtrsim 150\) times deeper in flux density than a deep far-infrared survey. By sampling redshifted hot dust and polycyclic aromatic hydrocarbon features, 24 µm surveys reveal a sample of galaxies which have significant dust in them and are likely to be contributing to the emission at far-infrared wavelengths due to the strong observed correlation between mid-infrared and far-infrared luminosities of galaxies (CE01). By stacking the far-infrared data at the positions of these 24 µm sources, the background limited noise \(\sigma\) can be reduced by \(\sigma/\sqrt{N}\) where \(N\) is the number of sources that are stacked on. In reality however, the flux from the wings of individual bright sources and from the uncertainty in

\textsuperscript{2}http://data.spitzer.caltech.edu/popular/fidel/
the subtraction of these brighter source results in an additional term, such that the noise in
the stacked image is:

\[
\sqrt{\sum_i \sigma_i^2 + \sigma_{conf,i}^2}
\]

with \(\sigma_{conf,i}^2\) being the variance in the residual map in the vicinity of the \(i^{th}\) source after it
has been fit and subtracted. If the sources are not subtracted from the map, then \(\sigma_{conf,i}\) is
simply the Poisson noise from the flux of the \(i^{th}\) source which is typically larger than the
variance in the residual map. Similarly, the extended wings of the point spread function
results in the stacked flux biased high as we will demonstrate in the next section. Thus, to
avoid contamination of the stacked flux, stacking should generally be undertaken on maps
in which the individual sources detected with high significance are fit for and subtracted.

Since stacking can only reveal average properties of the stacked sample of galaxies,
selecting a homogeneous sample of objects provide more illustrative results than stacking
a heterogeneous sample such as those selected at optical/near-infrared wavelengths. For
stacking at far-infrared wavelengths, 24 \(\mu m\)-selected sources are the preferred choice due
to their superior spatial resolution, depth and stable image quality compared to longer
wavelengths (Rieke et al. 2004).

Furthermore, extreme care must be taken to avoid counting the flux in the wings of
individual sources multiple times, an effect which is important at far-infrared wavelengths
with the large point spread function. Care must also be taken to include the clustering prop-
erties of the stacked sources in the error analysis which otherwise results in underestimates
of the uncertainty in the stacked flux.

2.1. Spitzer Far-Infrared Surveys

We use three extragalactic fields for our IGL analysis: GOODS-N, ECDFS and Extended
Groth Strip (EGS); all of which were observed at 24 \(\mu m\) as part of the GOODS Spitzer and/or
FIDEL Legacy surveys (P.I. Mark Dickinson). The depths of the Spitzer 24 \(\mu m\) data varies
from field-to-field. For consistency in our stacking analyses, we chose a 24 \(\mu m\) depth for
each field such that the completeness limits were comparable. These flux limits are listed in
Table 1. The 24 \(\mu m\) source catalogs are constructed using the positions of sources detected
at shorter wavelengths (3 – 8 \(\mu m\)) as priors (Magnelli et al. 2009a).
2.1.1. 70µm

We utilize a mosaic constructed using the public 70µm observations of the GOODS-N field taken as part of the FIDEL program in conjunction with deep observations described in Frayer et al. (2006). Since the combined mosaic covers the entire GOODS-N area, there is corresponding deep 24µm coverage over this mosaic. The total field size with deep coverage is 174.3 arcmin$^2$. The Spitzer beam size at 70µm is 18$''$ Full Width at Half Maximum (FWHM) while the beam size at 24µm is 5.7$''$ FWHM (Table II). At this spatial resolution, almost all extragalactic sources are point sources. Using positional priors from the much deeper 24µm data, Magnelli et al. (2009a) have used point source fitting to estimate the 70µm flux density of each 24µm source. Using extensive simulations, they have characterized the reliability and completeness of the FIDEL 70µm survey. The 80% completeness limit of the 70µm survey is 3 mJy although individual sources in unconfused regions can be detected down to fainter flux densities.

We first subtract all reliably detected sources from the 70µm mosaic. We do this by scaling the 70µm point spread function (PSF) to the flux density of each source and subtracting it off. The 127 reliably detected sources which have 70µm signal to noise ratios $> 6$ and which span a flux density range of 1.2 – 40.5 mJy are subtracted from the map. We conservatively choose 6σ because the noise is correlated in the final mosaics as a result of which the measured noise is biased low compared to the true noise. The exact magnitude of this effect is difficult to quantify due to the filtering of the individual 70µm frames before coaddition, but we expect it to be a factor of $\sim$2. These individually detected sources contribute a total IGL intensity of 1.92±0.2 nW m$^{-2}$ sr$^{-1}$. We then take the residual map with these sources subtracted and stack on the location of the remaining 1945 24µm sources spanning a flux density range of 20 – 910 µJy. We cut out a square region of width 84$''$ around the position of each source, starting with the one with the highest 24µm flux density. We then mask out a region of radius 16$''$ around the nominal position of the source in the map after including it in the stack. The cutouts are made in decreasing order of 24µm flux density. The masked region is exactly the size of the aperture used to measure the photometry and ensures that the flux in any particular pixel is not counted multiple times. To stack, we take a simple sum of the pixel values from the cutouts although we note that taking a sigma clipped sum does not result in any appreciable difference. Due to the mask, the image cutouts of faint 24µm sources which are in the vicinity of brighter sources will mostly have values of zero except for the unmasked pixels. However, since the pixel contribution from these faint sources have been included when making the cutout for the brighter source, we ensure we are not double counting the flux in any pixel. We obtain a strong detection in the resultant stack with an IGL intensity of 1.7±0.7 nW m$^{-2}$ sr$^{-1}$. After application of a 70µm calibration correction factor of 1.15, this implies the total contribution of the 24µm detected
sources to the IGL should be $4.2 \pm 0.7 \, \text{nW} \, \text{m}^{-2} \, \text{sr}^{-1}$ of which approximately half is from the directly detected $> 6\sigma$ 70 $\mu$m sources (Figure 1).

We note that the masking is a critical step in the stacking process. In the absence of masking, we would have counted the flux in the wings of brighter (but still undetected) sources and attributed this to faint sources. The IGL resulting from stacking the faint 24 $\mu$m sources would then have been $3.2 \pm 1.1 \, \text{nW} \, \text{m}^{-2} \, \text{sr}^{-1}$, about a factor of 2 bias in the contribution of the faint sources. After adding in the contribution of detected sources and the 1.15 calibration correction factor, the resultant IGL would have been found to be $5.9 \pm 1.1 \, \text{nW} \, \text{m}^{-2} \, \text{sr}^{-1}$.

The quoted uncertainties in the stacked quantities are derived by performing Monte-Carlo simulations whereby the positions of the 24 $\mu$m sources are randomly offset by an amount which is between 1 – 3 FWHM. This offset ensures that uncertainties in the stacked intensities due to imperfect subtraction of the brighter sources is taken into account. It also ensures that the intrinsic large scale clustering of 24 $\mu$m sources is preserved in the estimation of uncertainties. Using a random set of positions distributed across the entire map for the Monte-Carlo will underestimate the uncertainties due to these two effects. The 70 $\mu$m image is then stacked at these offset positions and combined by taking a simple sum. The process is repeated a 100 times and the standard deviation of the aperture flux, with all appropriate aperture corrections gives the uncertainty in the stacked value. We find that these uncertainty values are typically 5 times higher than what one would derive by stacking on completely random positions on the source subtracted map.

The stacked value can change depending on the following effects. As expected, the total stacked flux is sensitive to the size of the masking region. If the masking radius and correspondingly, the aperture for photometry, is increased to 35$''$, we find that the stacked flux decreases such that the total IGL, after adding the contribution of detected sources and calibration corrections, is $3.3 \pm 0.7 \, \text{nW} \, \text{m}^{-2} \, \text{sr}^{-1}$. The fraction of pixels that go into the stack is however reduced such that after completeness corrections, we obtain a similar IGL to the one estimated with a smaller masking radius (see below). Estimation and subtraction of a local background from each cutout before stacking only results in a change of 1% in the total IGL. Stacking on the 24 $\mu$m positions without sorting on 24 $\mu$m flux density does not result in a significant detection.

The masking procedure however only includes a fraction of the pixels which correspond to faint 24 $\mu$m flux sources contributing to the stack (Figure 1). For example, if all sources with 24 $\mu$m flux densities above 25 $\mu$Jy are considered, only 37% of the pixels of these sources are included in the stack while if the flux limit is increased to 57 $\mu$Jy, more than 54% of the pixels of the sources are unmasked and can be included. To correct for this, we need to
measure the contribution to the stacked flux from sources in bins of 24\,\mu m flux and divide
the stacked flux and uncertainty of each bin by the fractional number of pixels contributing
to the stack. We call this a completeness correction\(^3\). The differential contribution to the
IGL from 24\,\mu m sources in a flux bin \((f_1 < f_2)\) can be calculated only by stacking on all
sources brighter than \(f_1\) in decreasing order of flux, including masking, and then subtracting
the IGL derived from stacking on all sources brighter than \(f_2\). Simply considering sources
between \(f_1\) and \(f_2\) and stacking on a mosaic with no sources subtracted as has been un-
dertaken by Dole et al. (2006) overestimates the flux although the exact overcounting factor
depends on the relatively uncertain clustering properties of the faint sources around bright
sources. We find that stacking on the 838 sources with \(S_{24} > 74\,\mu Jy\), after application of the
completeness corrections shown in Figure 1 and appropriate calibration corrections account
for 4.9\pm0.5\,nW\,m\(^{-2}\)sr\(^{-1}\). The 1107 sources between 20 – 74\,\mu Jy only have one fifth of their
pixels included in the stack due to the masking. The differential contribution to the stacked
flux in this bin needs to be corrected upward by a factor of 5 yielding 2.1\pm0.9\,nW\,m\(^{-2}\)sr\(^{-1}\). Thus, our best estimate for the IGL from the data, including detections, masking, com-
pleteness corrections and calibration corrections is 7.0\pm1.0\,nW\,m\(^{-2}\)sr\(^{-1}\). We note that the
24\,\mu m catalog itself is 85\% complete in the faintest flux bins but we neglect application of
this second order completeness correction which would add 0.4\,nW\,m\(^{-2}\)sr\(^{-1}\) to the best IGL
estimate derived above.

An alternate technique that we adopt to measure any bias in our stacking technique is by
simulating the data. We input point sources into a simulated 70\,\mu m map at the locations of
the 24\,\mu m sources that we stack on. The 70\,\mu m/24\,\mu m flux ratios for these simulated sources
are derived from the CE01 model templates and the evolution of the infrared luminosity
function derived by Magnelli et al. (2009a). We also make sure that this map does not
contain any 6\sigma sources so we are trying to simulate our residual map which we use for
stacking. We then repeat the stacking procedure on this simulated image using no masking
and compared the stacked flux with the total input flux. We find that the stacked flux exceeds
the input flux by a factor of 1.2. Thus, using the simulations, we estimate that the IGL in
the maps is probably the sum of 1.92 (detected sources) and 3.2/1.2, which after calibration
correction factors implies 5.3\pm1.1\,nW\,m\(^{-2}\)sr\(^{-1}\)although the exact value may be susceptible
to the redshift distribution of the sources and the distribution of their 70\,\mu m/24\,\mu m flux
ratios.

Our analysis therefore suggests that the true 70\,\mu m IGL from 24\,\mu m galaxies brighter

\(^3\)There is a second completeness correction associated with the incompleteness of the 24\,\mu m catalog at
the faintest flux densities. Since we dont know the locations of those sources, we cannot include them into
the simulations.
than 25 $\mu$Jy is in the range $5.3 - 7.0$ nW m$^{-2}$ sr$^{-1}$, about 30% of which is due to galaxies that are individually detected in the 70 $\mu$m map.

A comparison with previous estimates of the 70 $\mu$m IGL reveals that Dole et al. (2006) estimated an IGL of $5.93 \pm 1.02$ nW m$^{-2}$ sr$^{-1}$ for source with $S_{24} > 60$ $\mu$Jy. By adopting a total EBL estimate of 6.4 nW m$^{-2}$ sr$^{-1}$, they claim that the bulk of the IGL is resolved. We next attempt to reproduce these measurements using an identical set of steps as described in the Dole et al. (2006) paper. We divide the 24 $\mu$m source list into flux bins and stack on the sources in each bin separately, with no masking. The stacking is performed on the maps which still have the individually detected sources in them as was done by Dole et al. (2006). We then add the contribution of the stacked measurement in each 24 $\mu$m flux bin and obtain a 70 $\mu$m IGL value of $7.1 \pm 1.4$ nW m$^{-2}$ sr$^{-1}$ for $S_{24} > 60$ $\mu$Jy (Figure 1). This is a significant overestimate since the stacking on the sources in the fainter flux bins includes sources which fall within the PSF of brighter sources. As a result, the flux in those pixels is counted multiple times. If we mask the sources as described earlier, we derive a value of $3.3 \pm 1.0$ nW m$^{-2}$ sr$^{-1}$ for sources with $S_{24} > 60$ $\mu$Jy which is significantly below the Dole et al. (2006) estimates. However, after completeness for the fraction of pixels missed and calibration corrections, this number rises to $5.4 \pm 0.5$ nW m$^{-2}$ sr$^{-1}$ as discussed above. Although the difference in the derived value compared to the Dole et al. (2006) estimate is not large, it is clear that a systematic bias is introduced depending on how the stacking is done. As we will demonstrate in the subsequent sections, this systematic bias gets larger with a larger point spread function. Thus, we believe that each of the steps: source subtraction, stacking on the residual maps with masking and simulations of the bias need to be performed to obtain a reliable stacked result.

Frayer et al. (2006) estimated the IGL by integrating over the 70 $\mu$m source counts distribution in GOODS-N, without stacking. They found that the contribution of directly resolved sources with $S_{70} > 1.2$ mJy is 4.3$\pm$0.7 nW m$^{-2}$ sr$^{-1}$. This is consistent with our values derived from stacking since it is simply an integral over a source counts distribution. Frayer et al. (2006) derive a total EBL of 7.4$\pm$1.9 nW m$^{-2}$ sr$^{-1}$ by adopting a power-law for the differential counts and extrapolating the source counts to zero flux.

The luminosity function of Magnelli et al. (2009a), if evolved between $0 < z < 1.3$, predicts a 70 $\mu$m IGL from $z < 1.3$ galaxies of 9.2 nW m$^{-2}$ sr$^{-1}$. This is using the CE01 far-infrared templates which has been shown by Magnelli et al. (2009a) to be a good fit to the 24$\mu$m/(1+z) and 70$\mu$m/(1+z) luminosities of galaxies. Thus, we conclude that the total EBL estimate of Frayer et al. (2006) is a significant underestimate. As we will discuss later, evolutionary models predict that the fraction of the 70 $\mu$m EBL which can be attributed to galaxies with $S_{24} > 25$ $\mu$Jy is $\sim$80% with a total EBL of 9.5$\pm$0.3 nW m$^{-2}$ sr$^{-1}$. Since our mea-
sured IGL from stacking is between $5.3 - 7.0\, \text{nW m}^{-2}\text{sr}^{-1}$, the deepest current observations at $70\, \mu\text{m}$ have resolved about $\sim 56$-75% of the EBL.

2.1.2. $160\, \mu\text{m}$

At $160\, \mu\text{m}$, we utilize the publicly released first epoch FIDEL data in the Extended Groth Strip. We analyze only the deepest 914 arcmin$^2$ which has a total exposure time of $>500$s at $160\, \mu\text{m}$. The corresponding coverage in the $24\, \mu\text{m}$ map is $>7200$s. Details of the $160\, \mu\text{m}$ mosaic are in Table 1. Starting with the $3.6\, \mu\text{m}$ catalog, we fit for the fluxes of the $24\, \mu\text{m}$ sources using the same technique as above and which is described in Magnelli et al. (2009a). We then apply a flux density cut of $100\, \mu\text{Jy}$ to the $24\, \mu\text{m}$ catalog. The coordinates of these brighter $24\, \mu\text{m}$ sources are provided as input to the point source fitting in the $160\, \mu\text{m}$ image. The uncertainty in the $160\, \mu\text{m}$ photometry of each source is estimated as the sum of the squares of the residuals in the $160\, \mu\text{m}$ map after all sources are fit and subtracted. We apply a signal to noise cut of $>5\sigma$ and $20\, \text{mJy}$ in the $160\, \mu\text{m}$ catalog for reliability. We find that these reliably detected $160\, \mu\text{m}$ sources contribute $1.4\pm 0.1\, \text{nW m}^{-2}\text{sr}^{-1}$. After subtracting out these sources, we stack at the positions of the remaining $24\, \mu\text{m}$ sources following the guidelines described earlier for the $70\, \mu\text{m}$ stacking. The public release of the $24\, \mu\text{m}$ EGS observations are relatively shallow compared to the GOODS-N data described earlier, but still deeper than the Spitzer observations used by Dole et al. (2006). We estimate the $24\, \mu\text{m}$ data in EGS is complete at $55\, \mu\text{Jy}$ depth.

Stacking on sources detected with high confidence in the $24\, \mu\text{m}$ map, including masking, results in a stacked $160\, \mu\text{m}$ intensity of $1.9\pm 0.3\, \text{nW m}^{-2}\text{sr}^{-1}$ implying a total $160\, \mu\text{m}$ IGL intensity of $3.3\pm 0.4\, \text{nW m}^{-2}\text{sr}^{-1}$. We note that the masking radius used (Table 1) is large compared to the FWHM of the PSF due to the fact that the PSF in the broad $160\, \mu\text{m}$ filter is more sensitive to the intrinsic spectrum of the source in the sense that red sources have broader PSFs than blue sources. To avoid missing flux, we use a larger aperture and correspondingly larger masking radius. If we had chosen not to mask the sources after including them in the stack, we would have derived a total stacked intensity of $11.8\pm 1.6\, \text{nW m}^{-2}\text{sr}^{-1}$ and a total IGL of $13.2\pm 1.7\, \text{nW m}^{-2}\text{sr}^{-1}$ after including the contribution of detected sources (Figure 1).

As we did for the $70\, \mu\text{m}$ data, we need to apply completeness corrections for the pixels of the stacked sources that have been masked due to their presence near a brighter $24\, \mu\text{m}$ source. The fractional incompleteness in the $160\, \mu\text{m}$ stacking at the same $24\, \mu\text{m}$ flux density is higher than at $70\, \mu\text{m}$ since the point spread function is larger (Figure 1). We find that the fraction of pixels included in the stack is 39% if all sources brighter than $S_{24} > 212\, \mu\text{Jy}$ are stacked
together. This number increases to 52% at 275µJy. Thus, after completeness corrections to the stacking analysis from sources with $S_{24} > 275\mu Jy$ and including the contribution of individually detected sources, we can account for $2.9\pm0.3\, \text{nW m}^{-2}\text{sr}^{-1}$ of the 160 µm IGL. We cannot account for the contributions of fainter 24 µm sources between $20 - 275\mu Jy$ since only 1.7% of the pixels from these sources are included in the stack. The resultant completeness corrections are large and unreliable although the stack from this small fraction of sources that can be stacked on does result in a significant detection.

We can however estimate a lower limit for their contribution by stacking down to the maximum flux limit $f_1$ such that the contribution of sources between $f_1$ and 275 µJy results in a significant stacked detection. We find that in the 24 µm flux density range of 125–275 µJy, we can get a measurement of the stacked flux although with a completeness correction factor of $\sim 14$. The resultant contribution to the IGL from sources in this bin, after completeness corrections, is $4.2\pm0.9\, \text{nW m}^{-2}\text{sr}^{-1}$. Thus, based on the stacking analysis as much as $7.1\pm1.0\, \text{nW m}^{-2}\text{sr}^{-1}$ of the 160 µm IGL may be resolved.

As we did for the 70 µm data, we attempt to simulate the 160 µm map to assess how large the bias is if we stack on the residual map with no masking. We input point sources using the 160 µm PSF at the locations of the 24 µm sources that we stack on. The 160 µm/24 µm flux ratios for these simulated sources are derived from the CE01 model templates and the evolution of the infrared luminosity function derived by Magnelli et al. (2009a). We then repeat the stacking procedure on this simulated image using no masking and compared the stacked flux with the total input flux. We find that the stacked flux exceeds the input flux by a factor of 1.4. Thus, using the simulations, we estimate that the IGL in the maps is probably the sum of 1.4 (detected sources) and 11.8/1.4, which implies $9.8\pm2.0\, \text{nW m}^{-2}\text{sr}^{-1}$ although the exact value may be susceptible to the redshift distribution of the sources and the distribution of their 160 µm/24 µm flux ratios.

We conclude that the measured 160 µm IGL derived from the deepest Spitzer maps is $3.3\, \text{nW m}^{-2}\text{sr}^{-1}$ although simulations and estimates of completeness at the faint flux bins yield a value between 7.1–9.8 nW m$^{-2}$ sr$^{-1}$. In comparison, Dole et al. (2006) estimate an IGL of 10.7±2.3 by stacking on sources with $S_{24} > 60\mu Jy$ from their shallower imaging data. We note that if we follow the Dole et al. (2006) stacking prescription in this field, we obtain a contribution of $15.0\pm2.0\, \text{nW m}^{-2}\text{sr}^{-1}$ from $S_{24} > 60\mu Jy$ sources. The overestimation in the stacking derived IGL at 160 µm due to the overcounting of flux in individual pixels is illustrated in the plots shown in Figure 1.

We also note that due to the large point spread function, it is not possible to reliably measure the contribution to the 160 µm EBL from sources below $S_{24} < 275\mu Jy$. At this flux level, less than 50% of the pixels from faint 24 µm sources contribute to the stacked flux
and the differential contribution from sources between $120 - 275 \, \mu Jy$ cannot be measured to better than $5\sigma$. Higher resolution data with Herschel will enable the contribution of fainter sources to be measured as described later.

The total EBL at $160 \, \mu m$ derived by Fixsen et al. (1998) using FIRAS data is $13.6 \pm 0.4 \, nW \, m^{-2} \, sr^{-1}$ while our models described later yield a value of $14.1 \pm 0.7 \, nW \, m^{-2} \, sr^{-1}$. Thus, the current observations have not resolved the $160 \, \mu m$ background.

### 2.2. BLAST Submillimeter Survey

BLAST is a 1.8m submillimeter telescope on a balloon, with detectors at three wavelengths: 250, 350 and 500 $\mu m$ (Pascale et al. 2008). BLAST completed a 11 day flight from Antarctica in December 2006 during which it took very deep images of the Extended Chandra Deep Field South (Devlin et al. 2009).

The BLAST data were released to the public in April 2009\(^4\). This release includes several versions of the signal and noise maps at all three wavelengths. The “decon.fits” files (hereafter referred to as the decon maps) have had a whitening filter applied to suppress the large scale frequencies – this affects the PSF and causes it to have negative structure and zero mean. The “smooth.fits” files have been convolved with the PSF in order to estimate the point source fluxes. Convolving with the PSF is equivalent to a minimum $\chi^2$ fitting of the PSF with the data (see Serjeant et al. 2003). This method is generally used to extract point sources in submm surveys as it increases the signal to noise ratio (SNR) and aids detection of faint ($> 3\sigma$) sources. However, this technique works under the assumption that a single PSF is a good fit to the data and may not be valid when there are blended and confused sources (it is only valid if there is $< 1$ source per beam, Serjeant et al. 2003).

Point source catalogs down to $3\sigma$ from these BLAST maps are given in Devlin et al. (2009). Information about the PSF and pixel scale for the BLAST maps is given in Table 1.

#### 2.2.1. 250, 350 and 500 $\mu m$

Unlike in the infrared, where stacking is done by excising cutouts of the image, coadding the cutouts and doing aperture photometry, in the submillimeter, stacking is usually done

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\(^4\)http://blastexperiment.info/results.php
on the smoothed (beam-convolved) maps where single pixel values, which contain the total flux of each source, are averaged to produce the stacked average (e.g. Devlin et al. 2009). This is primarily because of the complex beam shape which can have significant sidelobes. The sidelobes can contaminate the aperture photometry of other sources, resulting in a systematic uncertainty to the aperture flux which is dependent on the flux distribution and separation of the sources (See Appendix for details).

Although stacking on the BLAST maps has been presented in three separate papers (Devlin et al. 2009; Marsden et al. 2009; Pascale et al. 2009), there are certain improvements which can be made to the analysis presented therein. In Marsden et al. (2009) it is argued that stacking essentially boils down to taking the covariance of the map with the catalog. This simplification is true under the assumption that galaxies are not clustered. We know that IR luminous galaxies are clustered more strongly than optically selected field galaxies (Gilli et al. 2007). Although the clustering of IR luminous galaxies has been measured in redshift bins, it is the clustering strength of faint IR sources in the vicinity of brighter IR sources that is difficult to measure. We find that the surface density of 24 µm detected sources within a radius R (Table 1) of a 500 µm source brighter than 20 mJy is twice as high as the average surface density of 24 µm detected sources across the entire field (Figure 21 in the Appendix). Results from stacking are systematically biased high by this clustering. As a result, the stacking method employed by Devlin et al. (2009); Marsden et al. (2009); Pascale et al. (2009) will result in values biased high since the flux from the many clustered sources within each BLAST beam will essentially be counted more than once. Serjeant et al. (2008) estimated this over-counting of the stacked flux assuming a clustering strength and showed that it was significant even at the much smaller beam of SCUBA on the JCMT. There are several steps that can be taken to test and account for this effect of clustering on the stacked signal which we apply to our own BLAST stacking analysis below.

We perform our BLAST stacking analysis on both the decon maps where we stack cutouts and the smoothed maps where we stack single pixel values. We find consistent results between these two approaches. Values quoted in this paper are all for stacking image cutouts on the decon maps.

As described earlier for the 70 µm and 160 µm stacking analysis, we start off with the list of 24 µm sources cataloged for the ECDFS by Magnelli et al. (2009a). Building on the techniques presented for the Spitzer far-infrared data, we take three additional steps which many previous stacking analysis in the submillimeter have not accounted for:

- We fit the bright detected submillimeter sources and subtract their flux from the map. This residual map will then be used for the stacking analysis. The bright point sources leave a substantial footprint on the map which causes stacked fluxes to be overestimated
if they are left in the map. The contribution to the background from the detections
will be counted separately after doing the stacking analysis.

- We mask regions of the map as they are included in the stack. Again the large beam
means that there are many 24 µm sources per beam. If we don’t exclude regions of the
map that are already in the stack then flux in those regions will be counted more than
once.

- We perform simulations of confused maps with different source count distributions to
assess the presence of any bias in the stacked intensity values.

We calculate the uncertainties on all stacked quantities by doing Monte Carlo simu-
lations stacking random positions in the map. We performed 10000 trials of stacking $N$
galaxies (where $N$ is the number of galaxies in the catalog). The distribution of stacked
values from the 10000 trials is confirmed to be Gaussian centered around zero and we take
the standard deviation of the distribution as our uncertainty in the stacked flux.

*Subtracting the submillimeter detections*

In order to test the effects of bright sources on the stacked signals, we iteratively fit the
sources out of the map. Starting with the brightest 250 µm source, we fit the actual PSF
(including positive and negative structure) to the decon image at the source position and
remove the signal from the decon map. We continue to the next brightest source and so on.
For the positions of the detected sources we use the source lists from Devlin et al. (2009) down
to 4σ. After removing all the 250 µm emission from detected sources above a given SNR
threshold, we are left with a residual map (see Figure 2). The distribution of pixel values in
this residual map compared to the input map is shown in Figure 21 in the Appendix. We
stack this map on the 24 µm galaxies.

We calculate the total flux removed from the maps from the detected sources. Table
2 lists the contribution to the background from sources detected above 6, 5 and 4σ in the
central region of the BLAST maps that overlaps the deepest 24 µm coverage.

We note that there is no bias associated with estimating the contribution from the
detected sources separately from the stacked sources based on the covariance argument in
Marsden et al. (2009). The only complication associated with the subtraction of sources
from the maps might be flux boosting but since source subtraction is limited to the highest
SNR sources and we are fitting the full PSF (and not simply scaling to the peak flux), flux
boosting is expected to be much less of an issue.
The results of stacking on the residual maps are shown in Table 3 and Figures 4 (bar plots). Leaving the detected sources in the maps prior to stacking, results in a noticeable over estimate of the stacked flux as was shown for the 70 and 160 µm data. By simply subtracting the submillimeter detections prior to stacking we found that the IGL resolved by 24 µm-selected galaxies is ≲ 50% the total EBL at these submillimeter wavelengths. Stacking on the residual maps will still result in an overestimate since the flux surrounding sources < 4σ can still be double counted. We can’t subtract these sources individually but we can mask them so their flux is not counted multiple times.

Masking while stacking

We stack image cutouts from the BLAST maps centered on each 24 µm source which is not matched to a detected submillimeter source. Once a cutout is made from the map and added to the stack, these pixels are masked out in the original map so that the same flux cannot be counted more than once. We step through the 24 µm catalog in order of decreasing 24 µm flux since the brighter 24µm sources are expected to have higher 250 µm flux on average. We ensure that the mean of the map is zero prior to beginning our stacking analysis which means that we do not need to do any additional sky-subtraction from our stack.

We tried a range of cutout sizes and settled on the values given in Table 1 since those require a small aperture correction and doesn’t mask out too much additional flux. Assuming a perfect Gaussian beam with FWHM of 36″ at 250 µm (Marsden et al. 2009) this cutout size should include all flux within ±3 times the standard deviation of the Gaussian (in reality the beam is not a perfect Gaussian).

We measure the stacked flux from the cutout by fitting the actual PSF. This is better than fitting a simple Gaussian or doing aperture photometry since the negative sidelobes in the PSF is significant. We tested this on cutouts of detected 250 µm sources and found that it gave better results than aperture photometry or fitting a Gaussian (see Figure 19). From this test, we derive a negligible aperture correction of 1.02 to account for the emission outside the cutout area.

When masking while doing the stack, we are only able to stack a small fraction of the 24 µm sources. Since we are stacking in order of decreasing 24µm flux we can find the flux at which there is no regions of the map left to stack. The 24µm flux below which we begin to be incomplete is 600 µJy (see Figure 3). We note that this flux limit is comparable to that obtained at 160 µm (see Fig. 1) which is consistent since the beams are almost the same size. We also note that this is the flux limit where there are ~6 250 µm BLAST beams/source which is well past the standard confusion limit of 40 beams/source and even past the 7
beams/source limit where prior based source extraction techniques start to give inadequate results (Magnelli et al. 2009a).

As we did for the 70 and 160 µm analysis, we explored applying completeness corrections to the bins below 600 µJy. The stacked fluxes for the individual bins are however not significant and so we can’t reliably apply a correction to account for the sources we have had to mask. In a very wide area survey, where there are 100s of objects in each bin below 600 µJy then we could imagine applying a completeness correction to the masked stacking values to resolve more of the background. This will be possibly with Herschel where the beam is half the size so many more sources can be stacked with masking.

Our results from stacking with masking are shown in Table 3 and Figures 4. Since we are unable to apply completeness corrections, these values are lower limits to the true IGL from the 24 µm galaxies; the true value will lie somewhere in between the masking values and the no masking values. In addition, we expect the stacking with masking values will be biased low since we have only masked the positive emission in the zero-mean BLAST PSF and therefore are stacking on a map with a slight negative mean. From our masking analysis, we conclude that with the spatial resolution of the current data, the lower limit to the IGL from 24 µm selected galaxies between 250 – 500 µm is ∼10-15% of the total EBL shown in Table 5.

**Simulations**

We can further test how the stacking analysis might be biased by performing simulations where we know the IGL we put into the map (IGL\textsubscript{in}) and then we perform the same stacking procedure to see what we measure (IGL\textsubscript{out}). The ratio of these two quantities is then our over-counting or bias factor. This can give us an estimate of the true IGL coming from the 24 µm-selected galaxies.

We performed simulations of the BLAST 250 µm maps by doing the following (the same steps were repeated for the 350 and 500 µm maps as well):

1) Assign a 250µm flux to each 24 µm source using the full range of conversions from the CE01 galaxy templates. These sources are inserted into the fake map using the actual BLAST PSF at the real 24 µm positions so as to include the inherent clustering of this population in our simulation.

2) Add noise to the fake map according to the actual BLAST noise maps.

3) Subtracted any 4σ detections from the maps to create a fake residual map for stacking.
4) Perform stacking at positions of all input galaxies to get $\text{IGL}_{\text{out,nomask}}$.

5) The ratio of $\text{IGL}_{\text{in}} / \text{IGL}_{\text{out,nomask}}$ tells us how much we are over-predicting the stacked flux when we stack on the residual maps without masking. This bias factor is listed in Table 4.

6) We can also do the stacking with the masking to get $\text{IGL}_{\text{out,mask}}$ and the ratio $\text{IGL}_{\text{in}} / \text{IGL}_{\text{out,mask}}$ tells us how much we are under-predicting the stacking flux when we mask.

7) Iteratively determine the $\text{IGL}_{\text{in}}$ which reproduces both our observed $\text{IGL}_{\text{out,nomask}}$ and our observed $\text{IGL}_{\text{IN,mask}}$. This value is referred to as $\text{IGL}_{\text{corr}}$.

The value of $\text{IGL}_{\text{corr}}$ is an estimate of the actual background produced from the 24 $\mu$m galaxies (assuming all 250 $\mu$m detections have 24 $\mu$m counterparts) and is plotted as the blue circle in Figures 4 and given in Table 4.

We note that our values are significantly below the FIRAS determined EBL values as measured by Fixsen et al. (1998) and therefore conclude that $\sim$45-55% of the submillimeter background currently remains unresolved. This conclusion is different from that of Devlin et al. (2009) and Marsden et al. (2009) who do not do any masking or subtract the submillimeter detections prior to stacking. We have demonstrated that these two steps are crucial to ensure that the results are not biased due to overcounting the flux from multiple sources within the large beam because of the clustering of IR luminous galaxies. Aside from differing stacking techniques we also show later in this paper that we do not expect 24 $\mu$m-selected galaxies to resolve all the EBL since there are significant amounts of star formation coming from less luminous galaxies. We also note that the “completeness” corrections that Devlin et al. (2009) apply to the FIDEL 24 $\mu$m catalogs are small but incorrect. The completeness corrections they apply are based on much shallower data than the FIDEL data and the prior based cataloging technique used to generate the FIDEL 24 $\mu$m catalogs are less affected by confusion, resulting in higher completeness.

This bias factor listed in Table 4 provide a rough guide as to how much the stacked signal will overestimate the true value, if one does not correct for the contribution of multiple sources per beam due to the clustering of IR luminous galaxies. If all things were equal then this bias factor would only depend on the FWHM of the beam and the density of sources that are being stacking. However, in practice the bias factor will also vary depending on the wavelength since the dominant sources of the background change as a function of wavelength, on subtle differences in the PSF compared to a perfect Gaussian and on the clustering strength of the sources being stacked. For these reasons, these bias factors cannot be applied blindly to other far-infrared and submillimeter stacking analyses.
We repeated the above simulations with unclustered, random distribution of the 24 $\mu$m sources and found a bias factor of 1.00$\pm$0.06. This shows that the dominant effect in estimating the stacked fluxes of sources below the detection limit indeed arises from the clustering properties of the sources. If they were unclustered, there would not be a bias.

We also performed the above simulations without step 3 to test stacking biases without first subtracting the detections (as Devlin et al. 2009 and Marsden et al. 2009 have done). As expected, we find even higher bias factors than those listed in Table 4, with a value of 1.6 at 250 $\mu$m instead of 1.16. Factoring in this bias factor at 250 $\mu$m, we get $\text{IGL}_{\text{corr}} = 4.6 \pm 0.4$ nW m$^{-2}$ sr$^{-1}$ which is consistent with our best estimate of $\text{IGL}_{\text{corr}} = 5.2 \pm 0.5$ nW m$^{-2}$ sr$^{-1}$ from the 24 $\mu$m galaxies.

### 2.3. Cosmic Variance

Although the submillimeter stacking can only be undertaken with the deep BLAST observations taken in the ECDF-S, we can compare the stacking values at 70 $\mu$m between the GOODS-N and ECDF-S observations to assess if cosmic variance plays a significant role in different measures of the IGL. We choose only the central 777 arcmin$^2$ of ECDFS which has 70 $\mu$m coverage of at least half its peak exposure time. Using a procedure identical to that described earlier in Section 2.1.1, we find that the 179 individually detected $>6\sigma$ sources in the 70 $\mu$m map contribute 1.72 nW m$^{-2}$ sr$^{-1}$. Stacking on the remaining 6153 24 $\mu$m $>5\sigma$ sources in this region, down to a flux limit of 25 $\mu$Jy, yields a stacked intensity of 1.2$\pm$0.4 nW m$^{-2}$ sr$^{-1}$. After the factor of 1.15 calibration correction, we find a total IGL intensity in ECDF-S of 3.1$\pm$0.4 nW m$^{-2}$ sr$^{-1}$. If we had done the stacking without masking, we would have obtained a value of 2.4 nW m$^{-2}$ sr$^{-1}$ for the stacked intensity from the individually undetected sources, similar to the factor of 2 bias that we obtained in GOODS-N. Although there seems to be cosmic variance between the fields which results in a 26% lower IGL in ECDF-S than in GOODS-N, we conclude that our method gives consistent values for the IGL in the two fields.

### 3. The Evolution of the Infrared Luminosity Function

The evolution of the far-infrared luminosity function of star-forming galaxies has been measured very accurately at $z < 1.3$ (Magnelli et al. 2009a; Caputi et al. 2007; Le Floc’h et al. 2005). For each redshift, one can adopt a spectral energy distribution for galaxies as a function of far-infrared luminosity and calculate the observed intensity at each wavelength from
galaxies in each redshift bin. The sum of these observed intensities, integrated over all redshifts and luminosity, is the total EBL. By integrating between $0 < z < 1.3$, it is trivial to estimate what fraction of the EBL is directly attributable to galaxies at these redshifts and if that is consistent with the fraction of EBL that is resolved through stacking. We neglect the contribution of active galactic nuclei (AGN) since it has been demonstrated that their net contribution to the EBL is $< 10\%$ (Treister & Urry 2006).

The local IR LF is commonly represented as a double power-law (Sanders et al. 2003). This LF has a shape of:

$$
\phi(L) = \phi_0 \times \left( \frac{L}{L_0} \right)^{-0.6} : L < L_0
$$

$$
= \phi_0 \times \left( \frac{L}{L_0} \right)^{-2.15} : L > L_0
$$

where $L_0 = 10^{10.5} L_\odot$ and $\phi_0 = 10^{-2.5} \text{Mpc}^{-3}$. Our fiducial luminosity function extends down to $10^7 L_\odot$.

Magnelli et al. (2009a) use the deep 24 and 70 $\mu$m imaging data in the GOODS/FIDEL fields, in conjunction with spectroscopic and photometric redshifts to estimate the redshift evolution of the 24$\mu$m/(1+z) and 70$\mu$m/(1+z) luminosity function. By using a combination of direct detections and stacking at 70$\mu$m the luminosity function can be directly measured to fainter luminosities than before, thereby placing the first constraints on the faint end slope of the infrared luminosity function at $z \sim 1 - 2$. Magnelli et al. (2009a) fit model spectral energy distribution to the 24$\mu$m and 70$\mu$m luminosities of galaxies to estimate the total IR luminosity function. They have also shown that the CE01 templates provide an excellent fit to the observed 24 and 70 $\mu$m luminosities of galaxies at these redshifts. They find that the IR luminosity function shows rapid luminosity evolution as $(1+z)^{3.5\pm0.3}$ between $0 < z < 1$ but appears to flatten at higher redshifts (Magnelli et al. 2009b).

We attempt to constrain the evolution of the infrared luminosity function at $z > 1.3$ using the measured EBL as the primary constraint. In order to calculate the resultant EBL arising for different evolutionary histories for the infrared luminosity function, we need to adopt a far-infrared spectral energy distribution. CE01 provided a set of model spectral energy distribution for infrared luminous galaxies as a function of mid-infrared luminosity. Since the mid-infrared luminosity is correlated with the FIR luminosity, we can associate these templates with each luminosity bin in the LF to make extrapolations to the other wavelengths.
3.1. Constraints on Dust Enshrouded Star-Formation at $z > 1$: Modified CE01 Templates

We adopt the parametric evolution of Magnelli et al. (2009b) whereby $\phi_0$ evolves with redshift as $(1 + z)^{\alpha_D}$ while $L_0$ evolves with redshift as $(1 + z)^{\alpha_L}$. $\alpha_L$=3.5 between $0 < z < 1$ and $\alpha_D = -0.9$ between $0 < z < 1$. At higher redshifts, we leave the evolution as a free parameter and assess the range of evolutionary parameters that are consistent with the FIR EBL measured by FIRAS.

We adopt the luminosity dependent CE01 SEDs at $z < 1.3$. At $z > 1.3$ we apply the $(1 + z)^{3.5}$ luminosity evolution observed between $0 < z < 1$ to the CE01 SEDs. For example, at $z > 1.3$, we assume that a $L_{IR} = 10^{12} L_\odot$ galaxy has the SED of a $10^{12} \times 2.15^{-3.5} L_\odot$ in the local Universe. The reason we use 2.15 as the multiplicative factor is because the highest redshift bin in which the evolution is measured is $1 < z < 1.3$ and the mid point of the bin corresponds to a $1 + z = 2.15$. So, we scale the lower luminosity galaxy up by the ratio of the luminosities to represent a high redshift galaxy of a higher luminosity. We refer to these as the modified CE01 templates.

We find that at $z > 1$, if we keep $\alpha_L$=1.3, which is the tentative evolution measured at $1 < z < 2.3$ by Magnelli et al. (2009b), we find that $-3.2 < \alpha_D < -2.3$ to avoid overproducing the FIRAS measured EBL. This is shown in Figure 5. We also find that the luminosity function evolution measured at $z < 1.3$ accounts for $\sim 80-90\%$ of the total IGL between $60 - 160 \mu m$. This number drops to $\sim 67\%$ at $250 \mu m$, $55\%$ at $350 \mu m$ and $44\%$ at $500 \mu m$. The statistical uncertainty on these percentages are large since the absolute level of the background at $500 \mu m$ is not known to better than $30\%$ (Table 5).

We note that there exists a discrepancy between the FIRAS EBL (Fixsen et al. 1998) and the DIRBE measure EBL (Hauser et al. 1998) at $\lambda <<< 200 \mu m$. This difference is inconsequential to the evolution at $z > 1$ as can be seen by the range of EBL values spanned by the different star-formation rate densities in Figure 5. The evolution at $z > 1$ primarily affects the EBL values at wavelengths of $\lambda_{peak} \times (1 + z)$ where $\lambda_{peak}$ is the peak in the rest-frame far-infrared SED ($\nu L_\nu$) of galaxies. $\lambda_{peak}$ is $60 - 70 \mu m$ for starbursts like M82 and even for low-metallicity blue compact dwarf galaxies Engelbracht et al. (2008). Thus, any effect on the EBL from evolution between $1 < z < 6$ would be at $\lambda \sim 120 - 500 \mu m$ as has been discussed previously in CE01.

In an alternate scenario, we adopt the same luminosity function evolution as Magnelli et al. (2009b) at $z < 1$ but we recalibrate the luminosity evolution at higher redshifts to follow the extincted SFRD derived from the ultraviolet luminosity function of galaxies by Bouwens et al. (2009). This is simply the difference between their extinction corrected SFRD.
derived using the UV slope and the unobscured SFR from direct measurements of the UV luminosity function. This differs from the earlier calculation at $z > 1$ in that it assumes that the IR luminosity density is flat out to $z \sim 3$ and then declines monotonically between $3 < z < 6$. Both these trends for the evolution of the IR LF are shown in Figure 6. We find that using the CE01 templates, we always exceed the FIR EBL at $\lambda > 300 \mu m$ if we adopt a flat IR luminosity density between $1 < z < 2.3$ suggesting that the UV slope extinction estimates are too high.

Another constraint at $z > 1$ comes from the radio stacking analysis of Carilli et al. (2008) who found that at $z \sim 3$, the ratio of the radio derived star-formation rate density to the UV-derived star-formation for the galaxies at the bright end of the UV luminosity function is $1.8 \pm 0.4$. This implies that the dust obscured star-formation rate density is 0.8 times the star-formation rate derived from the observed UV values. Based on the Reddy et al. (2006) measure of the UV luminosity function, this translates to a dust obscured star-formation rate of $0.02 M_\odot yr^{-1} Mpc^{-3}$. Due to the relatively shallow depth of the rest-frame UV observations in this field compared to the UDF, the fainter galaxies, a fraction of which are likely to be the heavily dust obscured LIRGs and ULIRGs, are missed. As a result, the derived value is most likely a lower limit.

The range of possible constraints on the dust obscured star-formation rate density derived above are consistent with the Carilli et al. (2008) measurement. We thereby adopt an $\alpha_L = 1.3, \alpha_D = -3$ at $z > 1$ as the “best” model which is most consistent with the radio and the high redshift UV measurements of Bouwens et al. (2009), as well as the EBL constraints from FIRAS.

### 3.2. Constraints on Dust Enshrouded Star-Formation at $z > 1$: Cooler FIR Templates

Although the CE01 models have been shown to fit galaxy SEDs out to $z \sim 1.3$ (Magnelli et al. 2009a), there is evidence that due to the increased gas content of galaxies at higher redshifts, high redshift star-forming galaxy SED are different, more typical of scaled up low-luminosity starburst galaxies (Pope et al. 2008, 2006; Rigby et al. 2008). Another possible reason for the evolving SED might be the decreasing metallicity which might be responsible for a change in grain size distribution. The discrepancy between the MIR to FIR ratios appears to be most striking at $L_{IR} >> 10^{12} L_\odot$. Since these objects are only observed at $z > 1.3$, it is unclear if this is a luminosity effect or a redshift effect or if there is a strong observational bias since we can evaluate the properties of only the brightest, coolest galaxies at these redshifts (Murphy et al. 2009). We develop a revised library of SED in this paper which benefit from
the following observations:

- An extensive set of spectroscopic observations of infrared luminous galaxies in the LIRG and ULIRG regime with IRS (Pope et al. 2008; Murphy et al. 2009; Siana et al. 2009, 2008; Rigby et al. 2008; Armus et al. 2007; Desai et al. 2009).
- Deep 70 and 850 µm imaging in the GOODS/FIDEL fields which constrains the long wavelength spectral energy distribution of the most luminous sources (Pope et al. 2008; Murphy et al. 2009).
- Stacking results at 70 µm as a function of 24 µm luminosity at $z \sim 1$ and $z \sim 2$ (Magnelli et al. 2009a,b).

The data seem to suggest an increase in the MIR to FIR ratio of galaxies at high luminosities such that even the most luminous systems have large PAH equivalent width (Figure 7). However, there are strong selection effects associated with detecting these objects at high redshift. As a result, it is not clear if the observed galaxies span the entire range of dust temperatures and associated far-infrared colors or are just the most extreme sources. We note that an extensive set of spectroscopic observations of a sample of bright 24 µm source have been presented in Dasyra et al. (2009), but these have not yet been incorporated into our database. We adopt this revised set of SED only at $z > 1.3$ since galaxies at $z < 1.3$ appear to follow the CE01 templates quite well.

In Magnelli et al. (2009b), sources in the redshift bin $1.3 < z < 2.3$ were stacked at 70 µm as a function of 24 µm/(1+z) luminosity. It was shown that the CE01 templates overpredict the 70 µm/(1+z) luminosity of the galaxies in the sense that the far-infrared SEDs of these objects are too warm. A similar trend was found in Murphy et al. (2009) and Pope et al. (2008) although it was unclear if this is due to the fact that the sample was biased by the presence of submillimeter galaxies which might have cooler dust temperatures than average. We have modified the template SEDs to fit the observed trend between the 24 µm/(1+z) and 70 µm/(1+z) luminosity of the galaxies as discussed in Section 3.

These new templates are shown in Figure 8 and compare favorably with the stacked spectral energy distribution of $10^{13} M_\odot$ submillimeter galaxies at $z \sim 2.5$ for which we have high quality far-infrared constraints on the SED (Pope et al. 2008). We emphasize that these SED are our first attempt to constrain the $z \sim 1 – 2$ far-infrared SED of galaxies and further work is needed to assess if these can be used as reliably indicators of the bolometric correction in $z > 1.3$ galaxies.

We now evaluate constraints on the EBL using this set of cooler far-infrared templates that are in Figure 8.
We use the CE01 templates for galaxies at $z < 1.3$ but for $z > 1.3$, we adopt these new cooler far-infrared templates. For $z > 1$, if we keep $\alpha_L$ fixed at 1.3, then $\alpha_D$ must lie between $-2.8$ and $-2.0$ to be consistent with the EBL. Translating this to a dust obscured star-formation rate density using the canonical conversion factor of $1.71 \times 10^{-10} L_{\odot}$ for $1 M_{\odot} \, yr^{-1} \, Mpc^{-3}$, we derive the upper limits on the dust obscured SFR density as shown in Figure 9. A comparison with Figure 5 indicates that these values are somewhat higher than the values derived using the CE01 templates but still overlap substantially. The similarity between these estimates and the estimates in the previous section suggest that the constraints on evolution at $z > 1$ are not extremely sensitive to slight changes in far-infrared SED of galaxies at high redshift. We thereby adopt $\alpha_L = 1.3, \alpha_D = -2.0$ at $z > 1$ as our “maximal” dust obscured star-formation rate density model since it results in the highest star-formation rate density at $z > 1$ without violating the EBL values.

A useful consistency check on the model comes from the analysis of the 850 $\mu$m selected galaxy population by Wall et al. (2008). They found that submillimeter galaxies at $1.8 < z < 4$ have a surface density of $\sim 1800 \pm 600$ deg$^{-2}$ with the surface density at $z < 1.8$ being a factor of 5 larger. Based on the derived evolution at $z > 1$, we obtain a $z > 1.8$ surface density of $1100$ deg$^{-2}$ for the galaxy population with $S_{850} > 2$ mJy. Higher values for the surface density can be obtained simply by cutting off the faint end of the infrared luminosity function at $\sim 10^9 L_{\odot}$. Although the “maximal” evolution derived here is $\sim 2.5\sigma$ above the radio stacking constraint of Carilli et al. (2008), it indicates that the two models presented in this section and in Section 3.1 must straddle the entire range of $z > 1$ evolutionary histories for the IR luminosity function. These constraints on the dust obscured component of the star-formation rate density are compared with the unobscured star-formation rate density in Figure 10.

As we discussed in Section 3.1, we assess if it is possible to obtain consistency between these measurements and the UV slope estimates using the new templates. If the IR luminosity density is flat between $1 < z < 2.3$ such that it is consistent with the lowest redshift at which a dust correct SFRD is measured by Reddy et al. (2006) and Bouwens et al. (2009), then the decline of the dust obscured star-formation rate density with increasing redshift must necessarily be steeper than measured from the UV to avoid violating the FIRAS measurements. We find that if the decline starts at $z = 2.3$, then for $\alpha_L = 0, \alpha_D$ must lie in the range $-6 < \alpha_D < -3.4$. This factor of $\sim 4$ overestimate of the UV SFRD at $z > 2.3$ is most likely due to significant contribution of nebular emission to the SED of a young stellar population, an effect first noticed by Reddy et al. (2006); Siana et al. (2008). They concluded that for galaxies with $< 10$ Myr stellar populations, the UV slope and Meurer et al. (1999) relation overestimates the reddening partly due to the nebular emission and partly because the intrinsic colors of the stellar population are significantly different from the nom-
inal $\sim$100 Myr old stellar population template adopted as a benchmark for the intrinsic SED of a galaxy.

We next translate our constraints on the infrared luminosity density at $z > 2$ to an effective ultraviolet extinction for comparison with the extinction derived from the UV slope.

### 3.3. Evolution of Dust Extinction

It has previously been suggested by Carilli et al. (2008) that the dust corrections to the UV based star-formation rate density might be overestimates. Carilli et al. (2008) based their argument on the radio stacking of UV selected LBGs and found that at $z \sim 3$, the ratio of the radio derived star-formation rate density to the UV-derived star-formation is $1.8 \pm 0.4$. If this ratio is attributed to dust extinction, then the extinction value is a factor of $\sim 2 - 3$ lower than previous estimates which have found extinction corrections of $\sim$3-5.

We find that the range of values we derive for the dust obscured star-formation in the previous subsection are in agreement with the values derived by Carilli et al. (2008). Thus, we conclude that the UV slope derived star-formation rate values are overestimates and the radio and IR are giving consistent results. Moreover this decline in SFRD between $1 < z < 2.3$ is in agreement with the estimates derived from 70 $\mu$m stacking in Magnelli et al. (2009).

Based on these strong constraints from the EBL on the fraction of dust obscured star-formation at $z > 1$, we can utilize the measured UV luminosity density at these redshifts to predict the average extinction. We adopt the reddening-uncorrected UV luminosity density down to 0.04 $L_{\star,UV,z=3}$ measured by Bouwens et al. (2009) between $3.5 < z < 6$ and those measured by Reddy et al. (2006) at $1.9 < z < 3.4$. We adopt the “best” constraint on the dust-obscured star-formation rate density derived using the modified CE01 templates in section 3.1 with $\alpha_D$ at $z > 1$ of $-3.0$ although we provide uncertainties which span the range of possible FIR values derived from the analysis in Section 3.1 and 3.2. We use the prescription of Meurer et al. (1999) to convert the ratio of far-infrared to ultraviolet luminosity density to an ultraviolet extinction. This requires converting our total infrared ($8 - 1000 \mu$m) luminosity density to the far-infrared ($40 - 120 \mu$m) luminosity density used by Meurer et al. (1999). As discussed in CE01, this involves dividing the infrared luminosity by a factor of 1.92 for the galaxies in the IRAS Bright Galaxy Sample and so we apply the same ratio here. We have verified that this is a reasonable ratio to use even for the newer templates presented here by integrating the far-infrared SED over the relevant wavelength ranges although the conversion varies from $1.5 - 2.4$ depending on the color temperature of
the far-infrared emission.

Using the Meurer et al. (1999) conversion between the 1600Å extinction and the ratio of far-infrared luminosity to ultraviolet luminosity, we find that the upper limit to the dust obscuration at $z > 1$ imposed by the far-infrared EBL, results in extinction values that are systematically smaller than those derived from the UV slope. The discrepancy is the largest in the $2 < z < 4$ range where the difference between our extinction and the UV slope extinction is a factor of $\sim 2$ (Figure 11). There are two likely explanations for this. One possibility is that the increased fractional contribution due to nebular emission, which would have a relatively red SED, is making the UV slopes steeper. The other possibility is that the dust extinction law is changing due to the redshift evolution of dust grain sizes. For example, a Small Magellanic Cloud extinction law would decrease the ratio of the total to unobscured star formation rate estimate for a fixed value of the UV slope compared to the LMC or starburst extinction law which has been used to calibrate this relation (H. Shim, personal communication).

Reddy & Steidel (2009) have previously argued that at $z \sim 2 - 3$, the bulk of the star-formation occurs in faint, blue galaxies due to the steep faint end slope of the UV luminosity function. This is certainly plausible with the constraints on the dust obscured star-formation presented here. However, due to the uncertainty associated with converting UV-slope to extinction, errors are introduced in estimating dust obscured star-formation rate densities from the UV data. Current values derived from the UV are overestimates and should be reduced although the net effect on the comoving SFR measured by Reddy & Steidel (2009) is small. This would be in direct contrast to previous estimates of dust obscuration at $z \sim 2$, which indicate that ULIRGs dominate the comoving star-formation rate density. Furthermore, this is also in sharp contrast to the estimates at $z \lesssim 1.3$, where dust obscured infrared luminous galaxies account for $\sim 65\%$ of the comoving SFR density (Magnelli et al. 2009a; Chary & Elbaz 2001).

We also find good evidence for there to be an increase in average extinction with decreasing redshift between $2 < z < 6$. The extinction, which is correlated with dust content increases by a factor of 2 over this redshift range. Since the dust arises either from SNe or AGB stars (Dwek et al. 2007), the average dust content of the Universe must increase with stellar mass density. Over this redshift range, the stellar mass density has increased by a factor of $\sim 4$ suggesting that the dust content increases as the square root of the stellar mass density. In Chary et al. (2007b), it was shown that the average metallicity in star-forming galaxies increases as stellar mass density to the power $0.69 \pm 0.17$, over this redshift range. If metallicity were a proxy for dust content, the observed increase in extinction that we find in this paper, is consistent with the increase in metallicity that was found previously,
indicating that the two processes are unsurprisingly co-evolving.

3.4. Comparison between IGL Estimates from Models vs Stacking

We have used deep Spitzer imaging data at 24, 70 and 160 \( \mu \)m and submillimeter imaging from 250–850 \( \mu \)m to develop a reliable stacking procedure. In particular, we have been able to correct for the biases due to the clustering around bright detected sources in a model independent way. We have also used semi-empirical models for the evolution of the infrared luminosity function which is constrained by deep Spitzer imaging data at 24, 70 and 160 \( \mu \)m and the COBE measured EBL. These two independent lines of analysis should therefore give cross-consistent results on the estimates derived for the IGL. Figure 12 shows the values for the IGL derived from stacking compared with the EBL estimates derived from the model shown in Table 5. From the models, we have also estimated the fractional contribution to the EBL from LIRGs, ULIRGs and from bright 24 \( \mu \)m sources. We have used a different 24 \( \mu \)m flux limit for each panel depending on the sensitivity of the data used for the stacking analysis. Contributions from LIRGs and ULIRGs have been derived by integrating the luminosity function between \( 10^{11-12} L_\odot \) and \( > 10^{12} L_\odot \) respectively. These values typically would depend on the scatter in the far-infrared spectral energy distribution of galaxies. For example, if a subsample of galaxies were substantially cooler than average, they would result in a higher fraction at longer wavelengths, but a lower fraction at shorter wavelengths. We have therefore calculated the range for both the modified CE01 templates described in Section 3.1 and the newer templates presented in Section 3.2.

We find good agreement between the stacking values and the fractional contribution inferred from the evolution of the infrared luminosity function which gives us confidence that our conclusions are robust. There is seemingly a discrepancy at 160 \( \mu \)m since the stacked IGL is only \( \sim 20\% \), while stacking on all \( S_{24} > 55 \mu \)Jy sources should yield \( \sim 65\% \). This is due to the incompleteness from masking which as shown in Section 2.1.2 implies that we cannot stack below a 24 \( \mu \)m flux density of 275 \( \mu \)Jy. At a flux limit of 275 \( \mu \)Jy, the model reveals that we should obtain only about \( \sim 30\% \) of the background, exactly what we derive from stacking. If we instead use the IGL value of 9.8 nW m\(^{-2}\) sr\(^{-1}\) that we get from simulating the 160 \( \mu \)m map with 24 \( \mu \)m sources down to 55 \( \mu \)Jy, we find that we would have resolved \( \sim 70\% \) of the EBL, in excellent agreement with the model.

For future reference, we have also plotted the fraction of the EBL that would be resolved by stacking on 850 \( \mu \)m and 1.2mm maps. We note that Wang et al. (2006) have attempted stacking analysis on the 850 \( \mu \)m maps without subtracting the detections or masking. As discussed earlier, this results in severe overestimates of the stacking values and thereby the
derived IGL. A stacking analysis following similar techniques presented in this paper at these longer submillimeter wavelengths will be presented in Penner et al. (in preparation).

We show in Figure 13 the fractional contribution to the EBL at different wavelengths as a function of infrared luminosity. The largest contribution to the EBL arises from galaxies with luminosities between $10^{10.5}$ and $10^{11.5}\, L_\odot$. Ultraluminous infrared galaxies with $L_{\text{IR}} > 10^{12}\, L_\odot$ contribute $\sim 5 - 15\%$ of the total EBL at any wavelength. In Figure 14, we plot the same quantity as a function of redshift which shows that the majority of the far-IR EBL comes from galaxies at $z < 1.5$.

4. Predictions for Herschel

Deep extragalactic surveys will be undertaken with the Herschel PACS and SPIRE instruments between 70 and 500 $\mu$m as part of the Guaranteed Time surveys and the Guest Observer Legacy surveys. Using the derived constraints on the evolution of the far-infrared luminosity function of galaxies at $z > 1$, we can make predictions for the redshift distribution of far-infrared detected galaxies as a function of flux density and the fraction of the EBL resolved by these sources.

4.1. Redshift Distribution

We utilize both sets of templates, the modified CE01 and the new templates presented here to predict redshift distribution of sources as a function of far-infrared flux density. As discussed in Section 3.1 and 3.2, these correspond to our “best” model and “maximal” model. The redshift distributions are shown in Figure 15. The deepest Herschel surveys have the potential to detect dusty ultraluminous infrared galaxies out to $z \sim 6$ (solid curves), although the deep 500 $\mu$m survey with BLAST has potentially detected candidate objects in the $z \sim 4 - 5$ regime (dashed curves). Cross-identification and spectroscopic confirmation of these sources is likely to be difficult. Beyond $z \sim 3$, the PAH features get redshifted out of the 24 $\mu$m bandpass as a result of which the 24 $\mu$m is a weak tracer of dusty galaxies at the highest redshifts. A deep 1.4 GHz radio survey of $\sim 15\, \mu$Jy depth will be required to identify the counterparts of these galaxies, assuming the local radio-infrared correlation is valid at those redshifts. However, the surface density of $z > 4$ galaxies detected at 500 $\mu$m is likely to be low. We anticipate that there are $\sim 2-9$ such sources per GOODS field which covers about 0.046 deg$^2$.

Regardless, the shape of the redshift distribution of sources shows a peak around $z \sim 1$–
2 and then declines rapidly. This is broadly similar to the redshift distribution presented in Valiante et al. (2009) for Herschel surveys which is unsurprising since their star-formation rate density is quite similar to that shown in Figure 7 and 8. Our number counts appear to be quite similar to their estimates as well. At a 100\(\mu\)m flux density limit of 1.5 mJy, Valiante et al. (2009) predict >10\(^4\) sources per square degree while we predict 1.4×10\(^4\) deg\(^{-2}\). At longer wavelengths though, significant discrepancies creep in. Above a 350\(\mu\)m flux density limit of 6 mJy, Valiante et al. (2009) predict \(\sim 10^4\) deg\(^{-2}\) while we predict 2500 – 3500 deg\(^{-2}\) where the range of values arise from our “best” model and “maximal” model. In comparison, Patanchon et al. (2009) derive a source density of \(\sim 2900\) deg\(^{-2}\) above 6 mJy from a P(D) analysis of the BLAST maps. Similarly at a 500\(\mu\)m flux density limit of 5 mJy, Valiante et al. (2009) predict 5000 deg\(^{-2}\) while we expect 1000 – 1500 deg\(^{-2}\). Patanchon obtain \(\sim 2000\) deg\(^{-2}\) at the same limit. The origin of this difference between Valiante et al. (2009) and our analysis is likely because their fits pass through the upper range of values in the submillimeter source counts since they adopted a flat evolution for the infrared luminosity density between \(z \sim 1 – 2\) while our estimates favor a decline at \(z > 1\). Their estimate should have resulted in an overproduction of the EBL although it is unclear from their Figure 16 whether their measurement is in agreement with the FIRAS limits.

We conclude that both our estimates for the redshift distribution are in agreement but that we require a slightly steeper evolution for the \(z > 1\) dust obscured star-formation rate to ensure consistency with the FIR EBL which results in lower source counts at the longest Herschel wavelengths.

### 4.2. Fraction of EBL Resolved

Direct detections with Herschel, even with the deepest extragalactic surveys such as GOODS-H, will resolve only a fraction of the total FIR EBL as shown in Figure 10. This fraction is 80%, 48%, 39%, 29% and 12% from sources brighter than flux density limits of 0.6, 5, 4.2, 6 and 5 mJy at the following wavelengths: 100, 170, 250, 350 and 500\(\mu\)m. However, the superior spatial resolution of Herschel compared to either Spitzer or BLAST will alleviate the effect of confusion noise and allow stacking to be done down to fainter limits than presented here. As shown in Figure 12, stacking exclusively on 24\(\mu\)m galaxy samples is unlikely to result in significant improvement compared to the IGL estimates presented here since the fraction of the EBL that comes from the sample of 24\(\mu\)m selected galaxies has been estimated to be \(\sim 40 – 60\%\) and are already in agreement with our values derived from simulating the maps. Alternate possibilities such as stacking on near-infrared selected samples of sources will have to be investigated while ensuring that color cuts are used to
select the dusty sources from the sources that are not actively star-forming. We estimate that by stacking on 100s of dusty galaxies in differential flux bins identified through their optical to near-infrared colors, we can achieve noise values that are a factor of 10 below the direct survey limits quoted above. At these depths, the models indicate that 95%, 83%, 82%, 71% and 68% of the background at 100, 170, 250, 350 and 500 µm will be directly resolved which will be a significant improvement on the values quoted in Table 4.

5. Implications for Zodiacal Light Models and the Near-Infrared Extragalactic Background Light

Given the consistency between our stacking analysis and the model for the evolution of the infrared luminosity derived based on the work by Magnelli et al. (2009a), we feel confident to compare the EBL estimates at $\lambda < 140$ µm derived from DIRBE data with the model estimates. As can be seen in Table 5, at these wavelengths, there is a significant discrepancy between the DIRBE estimates and the models. Constraints from the detection of TeV photons from blazars have excluded the possibility that the high value of the EBL at 60 µm is due to an extragalactic source population. It is also clear that there is no unusual source population in the deep 70 µm data that can account for the higher value of the 60 µm EBL. The most likely origin for the discrepancy is likely to be the zodiacal dust cloud. By comparing our model IGL intensities with these DIRBE EBL values, we attempt to constrain the origin of this excess emission.

The interplanetary dust cloud, or zodiacal dust, is made up of dust from asteroid and comets. The thermal component of emission from the zodiacal cloud which dominates at $\lambda > 3.5$ µm and the sunlight scattered off the cloud at shorter wavelengths are the primary sources of foreground emission at infrared wavelengths. Models that have been developed for the zodiacal light have utilized the time varying component of the emission as the Earth revolves around the Sun (Reach et al. 2003; Kelsall et al. 1998; Wright 1998). These three dimensional models broadly indicate that the dust has a temperature of $\sim 250$ K with a characteristic distance of $\sim 1$ Astronomical Unit (AU) from the Sun, although the exact values are a function of ecliptic latitude. Using the temporal variation of the emission however, provides poor constraints on the isotropic component of the zodiacal emission (Dwek et al. 2005).

Wright (1997) tried to constrain any additional component of zodiacal light by applying the “very strong no zody” condition which states that the high Galactic latitude 25 µm intensity, where the zodiacal emission peaks, should be constant and zero in one of the DIRBE observations. Although this increased the contribution of zodiacal light emission to
the diffuse intensity at both near- and far-infrared wavelengths, the resultant extragalactic background light at near-infrared wavelengths was still substantially in excess of the intensity obtained by adding the light from individually detected galaxies (Levenson & Wright 2008). For example, at 3.6 $\mu$m, corresponding to a minimum in the intensity of the zodiacal light emission, the integrated galaxy light is thought to be $\sim 5.7 - 9$ nW m$^{-2}$ sr$^{-1}$ (Fazio et al. 2004; Levenson & Wright 2008) while the EBL, using the "very strong no zody" condition is $13.3 \pm 2.8$ nW m$^{-2}$ sr$^{-1}$ (Levenson et al. 2007). The discrepancy at shorter wavelengths i.e. 1.2 and 2.2 $\mu$m, is larger, which may be a result of the increasing contribution from the zodiacal dust scattering of direct sunlight (Cambrésy et al. 2001).

The discrepancy at near-infrared wavelengths that is discussed in the literature, combined with the difference between the EBL and the IGL at far-infrared wavelengths suggests a common origin for the emission. In Figure 17, we plot the difference between the IGL and the EBL at both near- and far- infrared wavelengths. The discrepancy is maximum at 60 $\mu$m, with a decreasing contribution out to 240 $\mu$m. Although, the significance of the discrepancy at any one wavelength varies from 2.9$\sigma$ at 60 $\mu$m to 1.1$\sigma$ at 240 $\mu$m, the combined intensity between 60–240 $\mu$m is significant at the 3.2$\sigma$ level after including the systematic error associated with the evolution of the far-infrared luminosity function. As a result, this discrepancy is considered significant enough to warrant further investigation.

As shown in Figure 17, the spectrum of this excess emission is inconsistent with the spectrum of the thermal emission in the zodiacal light models. The spectrum is substantially redder than the zodiacal emission between 60 – 240 $\mu$m. Even if we fit only the excess at the most significant data point, at 60 $\mu$m, by zodiacal emission, it falls short of explaining the difference between the IGL and EBL at both 1.2 and 2.2 $\mu$m although the discrepancy at each of the wavelengths is only slightly larger than 1$\sigma$. The chi-square fit to the residual using the standard zodiacal model template results in a $\chi^2 \sim 300$ suggesting that incorrect zodiacal light subtraction cannot be responsible for the entirety of this residual emission.

We estimate the temperature of the blackbody corresponding to this extra component of emission. We find that the excess emission can be well fit by a blackbody of 53 K with a 95% confidence interval of 16 K. Due to the low significance of the discrepant emission, we do not attempt to constrain the emissivity of the blackbody although we note that the best fit with emissivity as a free parameter is consistent with an emissivity index of zero. The total thermal emission from this component is a mere 0.4% of the main zodiacal emission in even a dark field like the GOODS field and therefore could easily have been missed. The best fit temperature implies that this component is most likely in the outer solar system and probably arises from either the Kuiper Belt region or from outgassing of comets as they travel past their perihelion point along their orbit (Chary & Schlichting, in prep.). The existence
of such a component has previously been suggested by Stern (1996) although the search for such a component in DIRBE data has previously been limited to low ecliptic latitudes where the component is thought to be most significant (Backman et al. 1995).

We now assess what the albedo of this component has to be to account for the discrepancy between the integrated galaxy light and the EBL at near-infrared wavelengths. At 1.2 \( \mu \)m, we adopt the EBL values of Cambrésy et al. (2001), while at 2.2 and 3.6 \( \mu \)m, we adopt the EBL estimates of Gorjian et al. (2000), which are consistent with the more recent estimates of Levenson & Wright (2008). For the integrated galaxy light, at 1.2 and 2.2 \( \mu \)m, we adopt the values of Cambrésy et al. (2001). At 3.6 \( \mu \)m, we adopt the mean of the estimates by Fazio et al. (2004) and Levenson & Wright (2008). Table 5 summarizes the measurements. We find that if we assume the Kuiper Belt dust has the same grain size distribution as the zodiacal dust cloud, the albedo of the grains has to be \( \sim 4-5 \) times greater than the zodiacal light to reproduce the discrepancy in the NIR background, assuming that the grains are at \( \sim 40 \) AU. Since the grains in the zodiacal dust cloud are thought to have a NIR albedo of \( \sim 0.2 \) (Kelsall et al. 1998; Wright 1998), the high implied albedo of \( \gtrsim 0.8 \) for this component of emission is consistent with grains that have an ice mantle. Remarkably, with a change in a single parameter, the albedo, we are able to simultaneously fit the difference between the EBL and IGL at all three NIR wavelengths.

We thereby conclude that there is evidence for the existence of a distribution of ice mantle grains at high ecliptic latitudes at a distance of \( \sim 40 \) AU, that is responsible for the discrepancy between the integrated light from galaxies and the cosmic infrared background light at both near- and far-infrared wavelengths. The total thermal emission from this component is \( \gtrsim 25 \) nW m\(^{-2}\) sr\(^{-1}\), which is a small fraction of the zodiacal light emission even in high ecliptic latitude regions of sky. The relative contributions of the different components are shown in Figure 18. Future work will reveal the origin and physical properties of grains contributing to this component of emission.

6. Conclusions

We have utilized data from the deepest far-infrared surveys currently undertaken to evaluate the fraction of the extragalactic background light that has been resolved into individual galaxies. By using a combination of direct detections and stacking on the imaging data, we demonstrate that more than \( \sim 50\% \) of the background currently remains unresolved at all wavelengths between 100 – 500 \( \mu \)m. The 70 \( \mu \)m IGL, after large completeness corrections however comprises \( \sim 75\% \) of the extragalactic background light derived from models for the evolution of the galaxy luminosity function. We also demonstrate that previous estimates
of the integrated galaxy light using stacking have significantly overestimated the values by multiple counting of the flux from clustered sources and provide steps through which these can be corrected.

We have then, extrapolated measurements of the infrared luminosity function measured at $z < 1.2$ to higher redshifts and use the resolved fraction of the background along with the DIRBE/FIRAS measured EBL to derive our best estimates of the dust obscured star-formation rate at $z > 1$. We find that the UV slope appears to overestimate the dust extinction at $z > 2$, most likely due to the significant contribution of nebular emission to the broadband ultraviolet photometry. We provide average measures of the extinction at these redshifts and find that the average extinction increases with decreasing redshift. If translated to an increase in dust content, this is consistent with the rate of increase in metallicity with redshift, suggesting that the two processes are co-evolving. We also quantify the fractional contribution to the far-infrared EBL as a function of both redshift and luminosity. We find that ultraluminous infrared galaxies contribute $\sim 5\%$ of the total EBL and that the bulk of the star-formation occurs in galaxies with luminosities $\sim 10^{10-11.5} L_\odot$. Finally, we use the difference between the EBL derived from our models and the DIRBE measured values to provide tentative evidence for a contribution from ice mantle dust in the outer solar system. This dust appears to have a total intensity of $\sim 25 \text{nW m}^{-2} \text{sr}^{-1}$ at high ecliptic latitudes and can account for the discrepancy between the IGL and EBL at both near- and far-infrared wavelengths.

We thank Benjamin Magnelli for his work on the ECDFS 24 and 70$\mu$m catalog. We are grateful to the BLAST team for making their data public. In particular, we thank Ed Chapin for advice on the BLAST data. We thank Louis Levenson for helpful suggestions on the use of zodiacal light models and William T. Reach for useful discussions regarding the use of these models. RC is very grateful to David Elbaz and Vassilis Charmandaris for hosting his sabbatical where the stacking analysis was first undertaken. AP acknowledges support provided by NASA through the Spitzer Space Telescope Fellowship Program, through a contract issued by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA.

7. APPENDIX

We compare the fluxes of sources measured in beam-convolved BLAST maps as measured by Dye et al. (2009) with the flux measured through aperture photometry in the un-convolved maps. We find that the aperture flux show a larger dispersion at fainter fluxes.
where the fractional contribution of other sources becomes increasingly significant (Figure 19). As a result, we choose to stack the pixel flux in the beam-convolved maps for the BLAST data.

We also compare the distribution of BLAST pixel value before and after sources are subtracted in Figure 20. Subtracting the individually detected sources removes the positive skew in pixel values and results in a map which is dominated by the sum of confusion and instrumental noise. We note that the confusion noise in the submillimeter data is symmetric around zero since the beam has significant negative sidelobes while in the far-infrared data, confusion noise will only have a positive skew.

We also assess how much of a role the clustering of galaxies affect the stacks by measuring the surface density of 24 \( \mu \text{m} \) detected sources in the vicinity of a bright 500 \( \mu \text{m} \) detected source and comparing that to the average surface density of 24 \( \mu \text{m} \) detected sources over the entire field. Figure 21 illustrates that the bright submillimeter galaxies have a factor of two overdensity of 24 \( \mu \text{m} \) detected galaxies within a radius R compared to the average surface density of such sources. This suggests that the 500 \( \mu \text{m} \) sources may be detected because it is the combined flux of the individual sources. It also indicates that when stacking at the positions of 24 \( \mu \text{m} \) sources, the 500 \( \mu \text{m} \) flux from the source will thus be counted twice unless the PSF is fitted and subtracted. Stacking on maps with sources still in it will result in a positive bias to the stacked results.

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This preprint was prepared with the AAS TeX macros v5.2.
Table 1: Description of the imaging data used for the stacking analysis.

| $\lambda$ (µm) | PSF FWHM (″) | Pixel size (″) | $R$ (pixels)$^a$ | Field   | $S_{24}/\mu$Jy$^b$ |
|----------------|---------------|---------------|------------------|---------|-------------------|
| 70             | 18            | 4             | 4                | GOODS-N | 25                |
| 70             |               |               |                  | ECDF-S  | 40                |
| 160            | 38            | 8             | 6.75             | EGS     | 55                |
| 250            | 36            | 10            | 4.5              | ECDF-S  | 40                |
| 350            | 42            | 10            | 5.5              | ECDF-S  | 40                |
| 500            | 60            | 10            | 7.5              | ECDF-S  | 40                |

$^a$ $R$ is the radius used for masking in the cutouts.

$^b$ Flux limit of 24 µm catalog used for stacking analysis.
Table 2: Contribution of detected far-infrared/submillimeter sources to the IGL.

| Detection level | $\nu I_\nu$ [nW m$^2$ sr$^{-1}$] |
|-----------------|---------------------------------|
|                 | 70 $\mu$m | 160 $\mu$m | 250 $\mu$m | 350 $\mu$m | 500 $\mu$m |
| 6$\sigma$       | 1.9 ± 0.2 | 1.1 ± 0.1  | 0.40 ± 0.01| 0.232 ± 0.004| 0.103 ± 0.002|
| 5$\sigma$       | ...       | 1.5 ± 0.2  | 0.60 ± 0.01| 0.356 ± 0.006| 0.155 ± 0.003|
| 4$\sigma$       | ...       | 2.0 ± 0.3  | 0.97 ± 0.01| 0.538 ± 0.008| 0.199 ± 0.003|
Table 3. Contribution of 24 µm sources to the IGL as estimated from the data.

| Method                                      | 70 µm  | 160 µm | $\nu I_\nu$ [nW m$^2$ sr$^{-1}$] | 250 µm | 350 µm | 500 µm |
|---------------------------------------------|--------|--------|----------------------------------|--------|--------|--------|
| Dole et al. 2006 (> 60µJy)                 | 5.9±0.9| 10.7±1.6|                                | ...    | ...    | ...    |
| Devlin et al. 2009                         | ...    | 7.9 ± 0.5| 4.5 ± 0.3                        | 2.0 ± 0.2|
| No subtraction/no masking$^a$                | 7.1±1.4| 15.0±2.0| 7.30 ± 0.46                      | 4.02 ± 0.24| 1.86 ± 0.14|
| Subtract 6σ/no masking                      | 5.9±1.1 (3.7)| 6.70 ± 0.40 (6.30) | 3.46 ± 0.22 (3.23) | 1.34 ± 0.11 (1.24) |
| Subtract 5σ/no masking                      | ...    | 13.2±1.7 (11.8) | 6.37 ± 0.36 (5.77) | 3.28 ± 0.20 (2.92) | 1.26 ± 0.11 (1.10) |
| Subtract 4σ/no masking                      | ...    | ...    | 5.84 ± 0.32 (4.87) | 3.08 ± 0.18 (2.54) | 1.20 ± 0.10 (1.00) |
| Subtract 4σ/masking                         | ...    | ...    | 1.44 ± 0.09 (0.47) | 0.72 ± 0.04 (0.18) | 0.223 ± 0.016 (0.024) |
| Subtract 5σ/masking                         | ...    | 3.3±0.4 (1.9) | 1.12 ± 0.10 (0.52) | 0.55 ± 0.05 (0.19) | 0.183 ± 0.019 (0.028) |
| Subtract 6σ/masking                         | 4.2±0.7 (1.96) | 0.97 ± 0.11 (0.57) | 0.45 ± 0.05 (0.22) | 0.138 ± 0.021 (0.035) |
| Subtract 6σ/masking$^c$                     | 7.0±1.0 (4.8) | ...    | ...    | ...    | ...    |
| No subtraction/masking                      | ...    | 0.71 ± 0.12 | 0.28 ± 0.06 | 0.056 ± 0.029 |

$^a$These are derived by following exactly the same procedure as Dole et al. and Devlin et al. to enable a direct comparison with their values.

$^b$In cases where we have subtracted the detections out of the map we add their contribution after stacking. Values in brackets are from stacking only.

$^c$Includes a completeness correction for faint galaxies which could not be stacked on. The completeness correction factor cannot be accurately determined for wavelengths other than 70 µm.
Table 4: Estimate of the IGL through stacking simulations. The bias factor is the ratio of stacked flux with no masking to input flux as determined from simulations of the residual images. Uncertainties on the bias factor reflect the range of templates used to convert between 24 $\mu$m and far-infrared flux and the noise in the maps. $\text{IGL}_{\text{corr}}$ is the estimated contribution to the background from 24 $\mu$m selected galaxies based on the simulations and has the contribution of individually detected sources added. Errors on $\text{IGL}_{\text{corr}}$ include measurement errors as well as uncertainty in the calibration.

| Wavelength ($\mu$m) | Bias factor | $\text{IGL}_{\text{corr}}$ [nW m$^{-2}$ sr$^{-1}$] | Fraction |
|---------------------|-------------|---------------------------------|----------|
| 70                  | 1.2 ± 0.1   | 5.3 ± 1.1                       | ~56%     |
| 160                 | 1.4 ± 0.1   | 9.8 ± 2.0                       | ~70%     |
| 250                 | 1.16 ± 0.05 | 5.2 ± 0.5                       | ~54%     |
| 350                 | 1.14 ± 0.05 | 2.8 ± 0.3                       | ~52%     |
| 500                 | 1.2 ± 0.06  | 1.0 ± 0.2                       | ~43%     |

*The higher bias factor for 250 $\mu$m compared to 350 microns can be explained by the extended wings of the PSF at 250 $\mu$m.*
| Wavelength $\mu$m | EBL Intensity nW m$^{-2}$ sr$^{-1}$ | Reference | IGL Intensity nW m$^{-2}$ sr$^{-1}$ | Reference |
|------------------|---------------------------------|-----------|---------------------------------|-----------|
| 1.2              | 54 ± 16.8                        | Cambrésy et al. (2001) | 9 ± 2                           | Cambrésy et al. (2001) |
| 2.2              | 22.4 ± 6.0                       | Gorjian et al. (2000)  | 7.2 ± 1.6                       | Cambrésy et al. (2001) |
| 3.6              | 11.0 ± 3.3                       | Gorjian et al. (2000)  | 5.7 – 9.0                       | Fazio et al. (2004); Levenson & Wright (2008) |
| 60               | 28.1 ± 7                         | Finkbeiner et al. (2000) | 7.6 ± 0.25 | Model; This paper |
| 70               | ...                              | ...        | 9.5 ± 0.25                      | Model; This paper |
| 100              | 24.6 ± 8.4                       | Finkbeiner et al. (2000) | 13.2 ± 0.5                     | Model; This paper |
| 140, 160         | 25 ± 7.0                         | Hauser et al. (1998)   | 14.1 ± 0.8                      | Model; This paper |
|                  | 12.6 ± 4                         | Fixsen et al. (1998)   |                                 |           |
|                  | 15.3 ± 6.4                       | Lagache et al. (1999)  |                                 |           |
| 240              | 14 ± 3.0                         | Hauser et al. (1998)   | 9.6 ± 0.9                       | Model; This paper |
|                  | 10.9 ± 3                         | Fixsen et al. (1998)   |                                 |           |
|                  | 11.4 ± 1.9                       | Lagache et al. (1999)  |                                 |           |
| 350              | 5.6 ± 1.7                        | Fixsen et al. (1998)   | 5.4 ± 0.8                       | Model; This paper |
| 500              | 2.4 ± 0.7                        | Fixsen et al. (1998)   | 2.3 ± 0.5                       | Model; This paper |
| 850              | 0.5 ± 0.15                       | Fixsen et al. (1998)   | 0.50 ± 0.14                     | Model; This paper |
| 1200             | 0.17 ± 0.05                      | Fixsen et al. (1998)   | 0.16 ± 0.05                     | Model; This paper |
Fig. 1.— Top Panel: The integrated galaxy light at 70 (left) and 160 μm (right) from sources brighter than a particular 24 μm flux threshold, as estimated from Spitzer data using different stacking methodologies. The solid black is the best estimate from the current data. The EBL from DIRBE at 60 and 140 μm is shown as the solid square, the EBL from FIRAS at 160 μm as the solid star while the model estimates presented in this paper are shown as the empty square. When bright sources that are individually detected are not subtracted and the stacking is done without masking out the pixels that are included in the stack, the total IGL is significantly overestimated due to overcounting of the flux (dotted line). Even after the sources are subtracted, stacking without masking results in the stacked intensity being biased high. After masking, large and uncertain completeness corrections are required to measure the IGL of sources below a 24 μm flux density value of 74 μJy and 275 μJy in the 70 and 160 μm images respectively. This is shown in the lower panels as the fraction of pixels attributed to sources in differential 24 μm flux bins, that are unmasked and can contribute to the stacked flux. Higher spatial resolution far-infrared data with Herschel will reduce the incompleteness due to masking and improve stacked estimates of the IGL from faint 24 μm sources. The solid black line in the left panel shows the 70 μm IGL after these completeness corrections are applied. At 160 μm, the completeness correction can only be applied above 275 μJy and results in values similar to the solid line. As a result, we omit it for clarity.
Fig. 2.— Subtracting the submillimeter detections from the maps prior to stacking. Images are 27' across. Circles have a radius of 45'' and indicate the positions of the 5σ detections. The left panel shows the raw (decon) 250 µm map and the right panel is the same map with the detections removed.
Fig. 3.— Distribution of 24 $\mu$m flux densities of sources that can be stacked on at 250 $\mu$m after masking. The grey solid curve shows all secure 24 $\mu$m detections in the ECDF-S and the black dashed curve is the flux distribution for the sources we are able to stack in the 250 $\mu$m map with masking. The vertical dotted line shows the flux at which we are no longer complete in our stacking with masking. With only a few tens of sources we do not obtain a detection when stacking differential bins below $S_{24} = 600$ $\mu$Jy. The dot-dash line is the flux distribution of sources from stacking with masking on a map with same spatial resolution as 250 $\mu$m with Herschel; with 100s of sources per bin Herschel will be able to constrain the contribution to the IGL from sources with $S_{24} = 20$–600 $\mu$Jy.
Fig. 4.— Contribution of 24 µm galaxies to the 250 (top left), 350 (top right) and 500 µm (bottom) submillimeter background. Light bars are the contribution of bright, individually detected submillimeter sources while dark bars are the contribution from stacking on 24 µm sources that are not associated with the bright submillimeter sources. The bottom axis indicated the signal-to-noise threshold down to which detected sources were subtracted from the maps. The bars on the left are for stacking without masking – these measurements will be biased high (as shown by the lower limit). The bars on the right are for stacking with masking – these measurements will be biased low (as shown by the lower limit). The blue data point is our best estimate for the background from all 24 µm sources ($S_{24} > 40$ µJy) derived by simulating the stacking experiment.
Fig. 5.— Constraints on the $z > 1$ far-infrared luminosity density, and thereby dust obscured star-formation rate from the extragalactic background light using the CE01 templates. The luminosity density at $z < 1$ is constrained directly by far-infrared observations presented in Magnelli et al. (2009a). The left panel shows different scenarios for the evolution of the far-infrared luminosity density while the right panel shows the resultant EBL (green lines) in comparison with observations. DIRBE estimates of the EBL are shown as blue stars while the red region is the FIRAS estimate of the EBL. Dashed lines are the early estimates of the far-infrared EBL from Puget et al. (1996). We allow for pure density evolution at $z > 1$, although density and luminosity evolution are degenerate as demonstrated in CE01. The solid black star in the left panel is the radio stacking estimate on $z \sim 3$ LBGs by Carilli et al. (2008). The dot-dash lines and points are estimates based on the UV-slope of galaxies from Bouwens et al. (2009). We find that the dust obscured SFRD cannot be as high as estimated by using the locally derived reddening prescription on UV slope estimates (Bouwens et al. 2009; Reddy et al. 2006).
Fig. 6.— The left panel shows three possible estimates of the dust obscured star-formation rate density between 0 < z < 6 (See text for details). The dot-dash lines and points are estimates based on the UV-slope of galaxies from Bouwens et al. (2009). The green lines in the right panel shows the inferred EBL if the SFR density were to evolve as in the left panel using the CE01 templates. Linestyles are preserved in the left and right panels in that the solid green line in the right panels corresponds to the solid black line in the left panel etc. The dust obscured SFRD estimated from the UV slopes appears to over predict the EBL by $\sim 1.5\sigma$ at $\lambda > 350\mu m$ suggesting that UV slopes overestimate dust obscuration at $z > 2.5$. The solid circles show the fraction of the FIR IGL which will be directly detected with Herschel; we will need to rely on stacking to resolve the rest of the background.
Fig. 7.— Ratio of the peak 7.7 $\mu$m PAH flux to the 9–11 $\mu$m flux as a function of infrared luminosity. The ordinate is effectively a measure of the 7.7 $\mu$m PAH equivalent width. Due to the difficulty in measuring the absolute continuum level in high redshift galaxies, we plot this ratio instead of an equivalent width. The solid black circles are local ULIRGs from Armus et al. (2007), empty cyan diamonds are $0.5 < z < 2.5$ infrared luminous galaxies (Murphy et al. 2009; Pope et al. 2008), empty stars are from Siana et al. (2009) and asterisks are from Rigby et al. (2008). The solid black line shows the CE01 templates which underestimate PAH equivalent width among the most luminous sources due to the increasing AGN contribution in local ULIRGs. The green dashed line are the Dale & Helou (2002) templates while the red dashed line are the Rieke et al. (2009) SED models. Neither of these models reproduce the observed trend as a result of which we use have developed revised SEDs that follow the observational trend plotted as the black diamonds.
Fig. 8.— Comparison between the SEDs developed here (solid line) to fit the mid-infrared properties of $z > 1.3$ galaxies versus the CE01 templates (dotted line). The high redshift galaxies that have been observed appear to show higher PAH equivalent width and cooler dust temperature which motivated the development of the new SEDs. However, it is unclear if this is a selection effect associated with the sensitivity of the existing far-infrared surveys. The IR luminosities of the plotted templates are $3.7 \times 10^{10}$, $2.8 \times 10^{11}$, $2.8 \times 10^{12}$ and $10^{13} L_\odot$. We note that the new $10^{13} L_\odot$ template is consistent with the stacked SED of submillimeter galaxies presented in [Pope et al.] (2008).
Fig. 9.— Same as Figure 5 but using the new cooler set of galaxy templates developed in this paper for objects at $z > 1.3$. The decline is marginally slower than for the modified CE01 templates.
Fig. 10.— The unobscured (blue hatched) and dust obscured (red hatched) star-formation rate density with cosmic time. The blue dotted line is a simple polynomial fit to the ultraviolet measured SFR densities in Schiminovich et al. (2005; Reddy et al. 2006; Bouwens et al. 2009) while the region around it spans the range of measured uncertainties. The red region is the obscured SFR density derived from our analysis. The constraints at $z > 1$ on the obscured SFR density are ambiguous. If the radio stacking point (Carilli et al. 2008) is robust, then the lower limit of the region would be the best estimate of the obscured SFRD while the UV slope estimates would suggest the upper line.
Fig. 11.— Our best estimate of the 1600Å ultraviolet extinction (solid squares) derived from the models presented here along with the range of values (grey regions) that are consistent with the EBL. Empty circles show the extinction derived from the UV slope by Reddy et al. (2006) and Bouwens et al. (2009) which would violate the FIRAS measured EBL estimates. The dust obscuration does increase by a factor of $\sim 2$ with decreasing redshift between $2 < z < 6$ which is not surprising since the dust content of the Universe must be correlated with the build up of the comoving stellar mass density which has increased by a factor of $\sim 4$ between $2.3 < z < 5$. 
Fig. 12.— Fractional contribution to the EBL as a function of redshift with each panel representing a different wavelength. In each panel, we show the cumulative contribution of LIRGs, ULIRGs and galaxies above the 24 μm flux limit used to perform the stacking at each wavelength. For example, the GOODS-N data where the 70 μm stacking was done are sensitive down to ~25 μJy while the ECDF-S data where the BLAST stacking was done is sensitive down to ~40 μJy. The exact contribution of each population is dependent on the choice of FIR SED and so we show the plausible range for each quantity as the shaded region between the dotted and solid lines. Also plotted are our estimates derived using stacking. The lower limit of the stacking point is the value derived by adding the individual detections to the stacked flux from other 24 μm sources, including masking. The upper limit is from adding the detection to the stacked flux using no masking. These limits are not measures of uncertainties, which are negligibly small but are provided to illustrate the difference in values if stacking is not done carefully. The best estimate IGL, including individual detections, stacking and with corrections for incompleteness and overcounting is plotted as the solid symbol. Except for 160 μm where we cannot stack below a 24 μm flux of 275 μJy due to
Fig. 13.— Fractional contribution to the EBL at different wavelengths as a function of IR luminosity, integrated over all redshifts. The dashed lines are for the CE01 templates as discussed in Section 3.1 while the solid lines are for the new templates presented in Figure 6. LIRGs and ULIRGs ($L_{\text{IR}} > 10^{11} L_\odot$) contribute about $\sim 35\%$ of the total EBL at $\sim 70 \mu\text{m}$ with the fraction increasing with increasing wavelength.
Fig. 14.— Fractional contribution to the EBL at different wavelengths as a function of redshift, integrated over all luminosities. The dashed lines are for the CE01 templates while the solid lines are for the new templates presented in Figure 6. More than \( \sim 70\% \) of the EBL at \( \lambda \lesssim 500 \mu m \) arises from galaxies at \( z < 1.5 \).
Fig. 15.— Predicted redshift distribution of deep far-infrared surveys between 100 and 500 µm. The solid lines are for a fainter flux density limit (e.g. deep Herschel surveys such as GOODS-H) while the dashed lines are for a brighter flux density (e.g. current BLAST limits) at the same wavelength. The black lines show the estimates based on the “best” estimate of the IRLF at z > 1 as discussed in Section 3.1. The blue lines show the upper limits based on the “maximal” evolution in Section 3.2 which are consistent with the FIR EBL.
Fig. 16.— Fractional contribution to the EBL from sources above a specific flux density at different far-infrared wavelengths. The solid line is for the “best” model while the dashed line is for the “maximal” model. The deepest surveys with Herschel such as GOODS-H (P.I.: David Elbaz) will reach flux density limits of ∼1-5 mJy. In order to resolve the bulk of the far-infrared/submillimeter EBL, we will have to stack hundreds of sources to achieve stacked flux density limits more than 10 times fainter than direct detection limits.
Fig. 17.— Left panel: The symbols show the discrepancy between the integrated galaxy light and the estimated value of the extragalactic background light at both near-infrared and far-infrared wavelengths. The solid line shows a single component of ice mantle dust, with an albedo of $\sim 1$, at a distance of $\sim 20-80$ AU that can reproduce the observed discrepancy. The dashed line shows the intensity of the zodiacal dust cloud in GOODS-N (ecliptic latitude $\sim 60$ deg) while the dotted line is the same zodiacal light spectrum scaled down by 0.1. The observed discrepancy between the IGL and EBL is inconsistent with arising from the main cloud and requires a second component of emission from the outer solar system. Right panel: Chi-square contours from fitting the far-infrared emission by a blackbody. The different colors show the 90, 95 and 99% confidence levels while the best fit shown as the black square is $\beta = 0, T = 53$ K.
Fig. 18.— Estimates of the relative contributions of the zodiacal dust and integrated galaxy light in a typical extragalactic field. The latter would be isotropic and independent of choice of field. A tentative estimate of the contribution from isotropically distributed dust in the outer solar system is also labeled as cometary dust. Also shown is the intensity of the cosmic microwave background.
Fig. 19.— Aperture correction for photometry on 250 μm image cutouts. Taking the > 4σ sources in the central deep region of the BLAST ECDFS map, we compare the flux from the catalog to that measured from fitting the PSF to 9 x 9 cutouts and derive a negligible aperture correction of 1.02. At faint flux densities, the confusion from other sources increases resulting in a large scatter.
Fig. 20.— Pixel distribution for raw (light gray) and residual (black) 250 $\mu$m signal maps.
Fig. 21.— Ratio between the number of 24 $\mu$m sources within a radius $R$ (see Table 1) of a BLAST 500 $\mu$m source and the average number of 24 $\mu$m sources expected within the same radius assuming a completely random distribution. The average is 2 (dashed line) and is independent of 500 $\mu$m flux density. This implies that when stacking at the positions of 24 $\mu$m sources, the flux from individual 500 $\mu$m sources will be double counted.