A CONDITIONAL LUMINOSITY FUNCTION MODEL OF THE COSMIC FAR-INFRARED BACKGROUND ANISOTROPY POWER SPECTRUM

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ABSTRACT

The cosmic far-infrared background (CFIRB) is expected to be generated by faint, dusty star-forming galaxies during the peak epoch of galaxy formation. The anisotropy power spectrum of the CFIRB captures the spatial distribution of these galaxies in dark matter halos and the spatial distribution of dark matter halos in the large-scale structure. Existing halo models of CFIRB anisotropy power spectrum either are incomplete or lead to halo model parameters that are inconsistent with the galaxy distribution selected at other wavelengths. Here, we present a conditional luminosity function approach to describe the far-IR bright galaxies. We model the 250 µm luminosity function and its evolution with redshift and model-fit the CFIRB power spectrum at 250 µm measured by the Herschel Space Observatory. We introduce a redshift-dependent duty cycle parameter so that we are able to estimate the typical duration of the dusty star formation process in the dark matter halos as a function of redshifts. We find that the duty cycle of galaxies contributing to the far-IR background is 0.3–0.5 with a dusty star formation phase lasting for ∼0.3–1.6 Gyr. This result confirms the general expectation that the far-IR background is dominated by star-forming galaxies in an extended phase, not bright starbursts that are driven by galaxy mergers and last ∼10–100 Myr. The halo occupation number for satellite galaxies has a power-law slope that is close to unity over 0 < z < 4. We find that the minimum halo mass for dusty, star-forming galaxies with L_{250} > 10^{10} L_⊙ is 2 × 10^{11} M_⊙ and 3 × 10^{10} M_⊙ at z = 1 and 2, respectively. Integrating over the galaxy population with L_{250} > 10^{9} L_⊙, we find that the cosmic density of dust residing in the dusty, star-forming galaxies is responsible for the background anisotropies ∑_{dust} ∼ 3 × 10^{-6} to 2 × 10^{-5}, relative to the critical density of the universe.

Key words: galaxies: star formation – infrared: diffuse background – large-scale structure of universe

Online-only material: color figures

1. INTRODUCTION

The total intensity of the cosmic far-infrared background (CFIRB) is now established with absolute photometry (Puget et al. 1996; Fixen et al. 1998; Dwek et al. 1998). This background originates from the UV and optical emission of young stars, absorbed by the dust in galaxies and then re-emitted in the infrared (IR) wavelengths. Deep surveys with instruments aboard the Herschel Space Observatory have started to resolve this background intensity between 100 and 500 µm to discrete galaxies based on resolved counts (Oliver et al. 2010; Clements et al. 2010; Berta et al. 2011). Unfortunately, even the deepest images of the far-IR sky using PACS and SPIRE are limited by source confusion. For example, at 250, 350, and 500 µm, only 15%, 10%, and 6% of the total background intensity is resolved to individual galaxies, respectively. Instead of individual detections, the fainter galaxies responsible for the bulk of the CFIRB intensity are studied with statistics such as P(D), the probability of deflections (Glenn et al. 2010), and P(k), the angular power spectrum of CFIRB anisotropies resulting from the correlated confusion noise (Haiman & Knox 2000; Knox et al. 2001; Scott & White 1999; Negrello et al. 2007; Ambard & Cooray 2007).

While attempts were made to detect the power spectrum of CFIRB with Spitzer-MIPS at 160 µm (Lagache et al. 2007) and a limited low signal-to-noise ratio detection with BLAST (Devlin et al. 2009) in Viero et al. (2009), the first clear detection of the CFIRB anisotropy power spectrum from 30 arcsec to 30 arcmin angular scales came from Herschel-SPIRE at 250, 350, and 500 µm (Amblard et al. 2011). This was soon followed by Planck measurements of the CFIRB power spectrum from 5 arcmin to degree angular scales (Planck Collaboration 2011). At the longer millimeter wavelengths, clustering of dusty galaxies can also be studied as part of the cosmic microwave background (CMB) secondary anisotropy studies, where a combination of signals contribute to the total power spectrum (Addison et al. 2011; Archidiacono et al. 2012). While the arcminute-scale ground-based CMB experiments and Planck can study the large angular correlations in the CFIRB at linear scales, the angular resolution of Herschel-SPIRE (Griffin et al. 2010) is such that the measurements probe the nonlinear scales and capture important information on how the dusty star-forming galaxies are distributed in the dark matter halos.

First predictions on the CFIRB anisotropy power spectrum concentrated on the linear power spectrum scaled by a bias factor (Scott & White 1999; Haiman & Knox 2000; Knox et al. 2001). Since those early studies, a popular approach to describe the large-scale structure galaxy distribution has been to connect galaxies to the underlying dark matter halo distribution (see review in Cooray & Sheth 2002). This halo modeling allows a way to describe the galaxy clustering power spectrum and correlation function through the halo occupation number describing the number of galaxies in a given dark matter halo as a function of the halo mass. Recent improvements in the halo model involve an occupation number description that takes into account the luminosity dependence of the satellites through what are now called conditional luminosity functions (CLFs; Yang et al. 2004; Cooray & Milosavljevic 2005; Cooray 2006a).

While an attempt was made to incorporate CLFs to describe the CFIRB power spectrum (Ambard & Cooray 2007; see recent work in Shang et al. 2011; Wang et al. 2011; Xia et al. 2012), this was based on a phenomenological model for the
number counts and luminosity functions (LFs) of far-IR sources (Lagache et al. 2003). The number counts and LF measurements from the Herschel Space Observatory now allow us to both improve the model and extract parameters of the underlying CLF description.

Separately, modeling of recent measurements of the CFIRB anisotropy power spectrum with Herschel and Planck and the dusty galaxy signal in CMB secondary anisotropy data is somewhat controversial. The best-fit parameters of the original study (Amblard et al. 2011) either had a power-law slope for satellites that was steeper than 1.3 or had a relation between the satellite mass scale $M_{\text{sat}}$ and the minimum halo mass $M_{\text{min}}$ such that $M_{\text{sat}} \sim (3–4) M_{\text{min}}$. The galaxy clustering measurements in the optical band show that the power-law slope is slightly less than 1 (Zehavi et al. 2004; Abazajian et al. 2005), while $M_{\text{sat}} \sim (15–20) M_{\text{min}}$ (Gao et al. 2004; Kravtsov et al. 2004; Zheng et al. 2005; Hansen et al. 2009; Shang et al. 2011). The issue is not limited to the Herschel power spectrum since similar conclusions can also be reached with fits to the Planck CFIRB power spectrum. Prior to Herschel, the low signal-to-noise CFIRB power spectrum reported by BLAST (Viero et al. 2009) required a halo profile that extends out to $\sim 4 r_{\text{vir}}$ to fit the data, leading to an overestimate of the mean density of dark matter in the universe relative to the value in $\Omega_m$ that normalizes the dark matter halo mass function.

While a power-law description of the CFIRB power spectrum out to $\ell \sim 2000$ is likely adequate for the dusty galaxy power spectrum in ground-based arcminute-scale CMB anisotropy data (Addison et al. 2011), a clear departure from the power-law was detected in the Herschel measurement out to $\ell > 10^4$, indicating the transition between the two-halo and one-halo term of galaxy clustering. A proper description of the Herschel CFIRB power spectrum must then move beyond the power-law fit to the data. We also refer the reader to Penin et al. (2012) and Bethermin et al. (2012) for more recent modeling of CFIRB, concentrating on the Planck-measured CFIRB power spectrum, and Xia et al. (2012) for modeling of both Planck and Herschel.

This paper is organized as follows: In Section 2, we outline the Herschel data used for this analysis. In Section 3, we present a revised CLF model for the CFIRB anisotropy power spectrum. We present our results in Section 4 and conclude with a summary in Section 5. Throughout this paper, we assume the fiducial cosmology for the $\Lambda$CDM model of WMAP-7 results (Komatsu et al. 2011).

2. DATA USED FOR THE ANALYSIS

The CFIRB angular power spectrum used for this analysis is the same as that of Amblard et al. (2011), taken from the Herschel Multi-tiered Extra-galactic survey (Oliver et al. 2010) with the Spectral and Photometric Imaging Receiver (Griffin et al. 2010) on board the Herschel Space Observatory (Pilbratt et al. 2010). While the measurements were reported for three wavelengths, we concentrate on the $250 \mu m$ angular power spectrum since it has the highest signal-to-noise ratio and the best resolution.

The LF data measured by Herschel are taken from Vaccari et al. (2010) at low redshifts ($z < 0.2$) at $250 \mu m$. The high-$z$ LF data extending up to $z = 4$ at $250 \mu m$ are from Eales et al. (2010) and Lapi et al. (2011). We use data from Eales et al. (2010) in two bins at $0.2 < z < 0.4$ and $0.4 < z < 0.8$. These LFs are based out of optical and near-IR photometric or spectroscopic redshifts for $250 \mu m$-detected galaxies in the GOODS-North field. To extend the $250 \mu m$ LFs to higher redshifts, we make use of the results from Lapi et al. (2011). These LFs are somewhat uncertain as they are based on the submillimeter photometric redshifts, which for each galaxy could have an error of at least $0.3$ in $\Delta z/(1 + z)$ (Harris et al. 2012). In any case, some of that uncertainty is captured by the errors of the LF. In the future with more exact LFs our model can be further improved.

The low-$z$ LF data are shown in Figure 1 (left), while the CFIRB angular power spectrum data are shown in Figure 2 (left). Figure 3 (left) shows the high-redshift LFs data.

3. HALO MODEL AND LUMINOSITY FUNCTION FORMALISM

The CLF model we use here to analyze the LF and $P(k)$ data is largely based on the model of Giavalisco & Dickinson (2001) and Lee et al. (2009). One of the main advantages of this improved description of a halo model is that it clearly connects the LF to clustering of galaxies, allowing one to simultaneously constrain the model parameters using both these observables. The connection between one point (LF) and two point ($w(\theta), P(k)$) is based on an explicit model of the galaxy luminosity–halo mass relation as a function of redshift. When compared to the standard halo model with galaxy statistics described by an occupation number, such a luminosity-based approach is capable of accounting for the fact that the luminous galaxies are more likely to be in more massive halos. Moreover, the CLF-based model description of Lee et al. (2009) is general enough to
reproduce a wide range of shapes for the galaxy luminosity–halo mass relation and its scatter. This is advantageous as the shape of this relation is expected to be different at far-IR wavelengths when compared to the same data at optical wavelengths.

The fundamental ingredients in this revised CLF model are the mass functions for halos and sub-halos and the galaxy luminosity–halo mass relation and its evolution. The probability density for a halo or a sub-halo of mass \( M \) to host a galaxy with luminosity \( L \) is modeled as a normal distribution with

\[
P(L|M) = \frac{\eta_{\text{DC}}}{\sqrt{2\pi}\sigma(L|M)} \exp\left[\frac{-(L - \bar{L}(M))^2}{2\sigma(L|M)^2}\right],
\]

where \( \eta_{\text{DC}} \) is the duty cycle factor related to the duration of the star formation in the halos (and is \( 0 \leq \eta_{\text{DC}} \leq 1 \)). More precisely, the duty cycle represents a measure of the duration of the star formation, \( \tau_{\text{SF}} \), relative to the time interval probed by the survey or the observations, \( \Delta t \). As discussed in Lee et al. (2009), the ratio \( \tau_{\text{SF}}/\Delta t \) determines the number of halos that can host a detectable galaxy and is hence related to the ratio between the number densities of galaxies and available halos to host such galaxies \( n_g/n_h \). This is precisely the duty cycle \( \eta_{\text{DC}} \) we have introduced above.

Note that this description of the duty cycle is different from the “duty cycle” reported by Shang et al. (2011) for dusty, star-forming galaxies in their halo/CLF modeling of the Planck CFIRB power spectra. In their work, the duty cycle is derived by comparing the measured shot-noise amplitude that dominates anisotropy power spectrum at small angular scales to a prediction of the expected shot noise given the number density of halos and the observed counts. Given that the shot noise is \( \int dS S^2 \frac{dn}{dS} \), where \( S \) is the flux density and \( \frac{dn}{dS} \) is the number counts, the shot noise quoted in their paper is weighted more toward the bright, rare sources. The model comparison by Shang et al. (2011) suggests a duty cycle that is close to one, suggesting that the CFIRB anisotropies are dominated by normal quiescent galaxies. Here, we provide a precise estimate of the duty cycle down to a specific luminosity and as a function of redshift.

In Equation (1), \( \sigma(L|M) \) is the scatter in the luminosity–mass relation. In this description, the scatter can be related to the nature of the star formation. High values for the scatter with respect to the mean luminosity \( L(M) \) imply a star formation dominated by starbursts, while low values for scatter, suggesting a fixed relation between halo mass and luminosity, are typical of quiescent, steady star formation (see also discussion in Lee et al. 2009).

The relation between the halo mass and the average luminosity \( L(M) \) is expected to be an increasing function of the mass with a characteristic mass scale \( M_0 \), and we can write
\[ \bar{N}(M) = L_0 \left( \frac{M}{M_{\odot}} \right)^{\alpha_f} \exp \left[ - \left( \frac{M}{M_{\odot}} \right)^{-\beta_f} \right], \quad (2) \]

and the scatter can be parameterized in a similar way,

\[ \sigma(M) = \sigma_0 \left( \frac{M}{M_{\odot}} \right)^{\alpha_s} \exp \left[ - \left( \frac{M}{M_{\odot}} \right)^{-\beta_s} \right]. \quad (3) \]

As already discussed by Lee et al. (2009), these parameterizations do not have a specific physical motivation (except for the requirement of being an increasing function of mass) but offer the advantage to explore a large range of possible shapes. We need to consider the total halo mass function that is the number density of halos or sub-halos of mass \( M \). The contribution of halos \( n_h(M) \) is taken to be the Sheth & Tormen relation (Sheth & Tormen 1999). The sub-halo term can be modeled through the number of sub-halos of mass \( m \) inside a parent halo of mass \( M_p \), \( N(m|M_p) \). The total mass function is then

\[ n_T(M) = n_h(M) + n_{sh}(M), \quad (4) \]

where \( n_{sh}(M) \) is the sub-halo mass function

\[ n_{sh}(M) = \int N(M|M_p)n_{sh}(M_p)dM_p. \quad (5) \]

We parameterize \( N(m|M) \) as in van de Bosch et al. (2005),

\[ N(m|M) = \frac{\gamma}{\beta \Gamma(1-\alpha_{sh})} \left( \frac{m}{M_{\beta_{sh}}} \right)^{-\alpha_{sh}} \exp \left[ -\frac{m}{M_{\beta_{sh}}} \right], \quad (6) \]

where

\[ \gamma = \frac{f_{sh}}{\Gamma(1-\alpha_{sh},1/\beta_{sh}) - \Gamma(1-\alpha_{sh},10^{-4}/\beta_{sh})}. \quad (7) \]

Here \( \Gamma(\cdot) \) is the incomplete gamma function and \( f_{sh} \) is the sub-halo mass fraction. As shown in van de Bosch et al. (2005), where the model is calibrated using numerical simulations, both the normalization and the slope of the sub-halo mass function are not universal and depend on the ratio between the parent halo mass and the nonlinear mass scale, \( M_\star \), defined as the mass scale where the rms of the density field \( \sigma(M,z) \) is equal to the critical overdensity required for the spherical collapse \( \delta_c(z) \). The term \( f_{sh} \) in Equation (7) is fitted by the relation

\[ \log([f_{sh}]) = [0.4(\log(M/M_\star) + 5)]^{1/2} + 2.74 \quad (8) \]

in numerical simulations, and we make use of it in this study.

The best-fit relation for the slope parameters \( \alpha_{sh} \) and \( \beta_{sh} \) found by van de Bosch et al. (2005) is

\[ \alpha_{sh} = 0.966 - 0.028 \log(M/M_\star), \quad (9) \]

and \( \beta_{sh} = 0.13 \), independent of \( M \). With this description the total number of free parameters in the CLF model is nine, with four parameters for the luminosity–mass relation in Equation (2), four parameters for the scatter in Equation (3), and the duty cycle parameter \( \eta_{DC} \).

If the same luminosity–mass relation applies to both halos and sub-halos, then the product \( P(L|M)n_T(M)dLdM \) gives the number densities of galaxies with luminosity \( L \) in halos or sub-halos of mass \( M \). The LF is then

\[ \phi(L)dL = dL \int dM P(L|M)n_T(M). \quad (10) \]

The formalism introduced above also allows us to construct the halo occupation distribution (HOD) in a simple way. The contribution of central galaxies is simply the integration of \( P(L|M) \) over all luminosities above a certain threshold \( L_0 \) either fixed by the survey or a priori selected so that

\[ \langle N_c(M) \rangle_{L \geq L_{\text{min}}} = \int_{L_{\text{min}}} L dL \int dM N(m|M)P(L|m). \quad (11) \]

The total HOD is then

\[ \langle N_{\text{tot}}(M) \rangle_{L \geq L_{\text{min}}} = \langle N_h(M) \rangle_{L \geq L_{\text{min}}} + \langle N_{sh}(M) \rangle_{L \geq L_{\text{min}}}. \quad (12) \]

The model described so far holds at a given redshift. The duty cycle parameter \( \eta_{DC} \) and the luminosity–mass relation with its scatter are expected to have a redshift evolution. Here, we are attempting to fit LF data at a variety of redshift bins between \( 0 < z < 4 \). To account for the redshift evolution of the parameters, we assume that the parameters that describe the low-redshift \( (z < 0.2) \) dusty galaxy population are different from those for the high-redshift galaxies. Moreover, the high-redshift data extend from \( z = 0.2 \) to \( z = 4 \) and are divided into six redshift bins. We thus fit a total of seven duty cycle parameters, one for each of the bins, and do not attempt to constrain the duty cycle variation with a parameterized approach on the redshift evolution. For the evolution of the galaxy 250 \( \mu \)m luminosity–halo mass relation we account for the possible redshift evolution by introducing another parameter, \( p_m \), and rewriting the mass scale \( M_\odot \) as

\[ M_\odot(z) = M_{\odot,z < 0.2}(1+z)^{p_m}, \quad (14) \]

where we allow the evolution to follow the assumed power-law form.

Once the HOD is defined, it is possible to calculate the one-halo and two-halo terms of the far-IR anisotropy power spectrum. First, we define the power spectrum in terms of redshift-dependent three-dimensional clustering and will later project them along the line of sight to calculate the angular power spectrum of CIVRSP anisotropies. Here, we assume that the central galaxy is at the center of the halo and that the halo radial profile of satellite galaxies within dark matter halos follows that of the dark matter given by the Navarro, Frenk, and White (NFW) profile (Navarro et al. 1997). The one-halo term is then

\[ P^{1h}(k) = \frac{1}{n_g^2} \int dM \langle N_T(N_T - 1)u(k, M)^2n_h(M) \rangle. \quad (15) \]

where \( u(k, M) \) is the NFW profile in Fourier space and \( n_g \) is the galaxy number density

\[ n_g = \int dM \langle N_h(M) \rangle n_h(M). \quad (16) \]
The second moment of the HOD that appears in Equation (15) can be simplified as

\[ \langle N_T(N_T - 1) \rangle \approx \langle N_T \rangle^2 - \langle N_b \rangle^2, \]

and the power index \( p \) for the NFW profile is \( p = 1 \) when \( \langle N_T(N_T - 1) \rangle < 1 \) and \( p = 2 \) otherwise (Lee et al. 2009). The two-halo term of galaxy power spectrum is

\[
P^{2h}(k) = \left[ \frac{1}{n_g} \int d M \langle N_T(M) \rangle u(k, M) n_b(M) b(M) \right]^2 \times P^\text{lin}(k),
\]

where \( P^\text{lin}(k) \) is the linear power spectrum and \( b(M) \) is the linear bias factor calculated as in Cooray & Sheth (2002). The total galaxy power spectrum is then \( P_g(k) = P^{1h}(k) + P^{2h}(k) \).

As the observations are anisotropies on the sky projected along the line of sight, the observed angular power spectrum can be related to the three-dimensional galaxy power spectrum through a redshift integration along the line of sight (Knox et al. 2001):

\[
C_{\ell}^{\nu'} = \int dz \left( \frac{dz}{d\chi} \right)^2 j_\nu(z) j_{\nu'}(z) P_g(\ell/\chi, z),
\]

where \( \chi \) is the comoving radial distance, \( a \) is the scale factor, and \( j_{\nu}(z) \) is the mean emissivity at the frequency \( \nu \) and redshift \( z \) per comoving unit volume that can be obtained from the LFs as

\[
\tilde{j}_{\nu}(z) = \int dL \phi(L, z) \frac{L}{4\pi}.
\]

This model does not rely on the assumption of a number counts shape or an evolution. We are able to directly model-fit the mean emissivity as a function of redshift.

4. RESULTS AND DISCUSSION

In the revised CLF model outlined above, in principle, we have 23 free parameters: 7 duty cycle parameters, 8 parameters for the luminosity–mass relation and its scatter at low redshifts, 7 parameters for the same relations at high redshifts, plus the parameter \( p_M \) for the \((1 + z)\) redshift evolution of the mass scale (Equation (14)).

Separately, the CFIRB power spectrum contains the contribution from Galactic cirrus, in addition to the extragalactic anisotropies traced by the faint, dusty galaxies. In Amblard et al. (2011), the authors accounted for this contamination assuming the same cirrus power-law power spectrum from measurements of IRAS and MIPS (Lagache et al. 2007) at 100 \( \mu \)m and extending it to higher wavelengths using the spectral dependence of Schlegel et al. (1998). Such a frequency scaling resulted in an overestimated cirrus correction, as noted by the Planck team (Planck Collaboration 2011) in their analysis of the CFIRB power spectrum compared to the Herschel power spectrum. This is primarily due to the fact that the cirrus is likely overestimated in Schlegel et al. (1998) as IRAS 100 \( \mu \)m also contains the extragalactic background intensity. To avoid biasing our power spectrum low by an overestimated cirrus correction, we refit the raw power spectrum data from Amblard et al. (2011). Here we adopt the same power-law cirrus fluctuation power spectrum used in Amblard et al. (2011), with \( P(k) \propto k^{-n} \) with \( n = -2.89 \pm 0.22 \) as measured by Lagache et al. (2007). However, we rescale the amplitude of the cirrus power spectrum with a dimensionless factor \( C_{250} \) that we keep as a free parameter and model-fit that as part of the global halo model. This implies another free parameter in our model, leading to a total of 24 parameters. Given the large volume of the parameter space, a Markov Chain Monte Carlo (MCMC) analysis (see below) through the full parameter space is very time consuming. Moreover, it is unlikely that the information carried by the current data is able to constrain such a large number of free parameters.

We hence simplify the analysis as follows. We first fit the low-redshift parameters to the \( z < 0.2 \) 250 \( \mu \)m LF measurements from Vaccari et al. (2010) by only varying the four parameters related to the luminosity–halo mass relation and the duty cycle at low redshift, \( \eta_{\text{DC}}(z < 0.2) \). We assume no scatter in the luminosity–mass relation. When fitting to high-redshift data, the total number of free parameters is 11:3 parameters for the \( L–M \) relation (\( \alpha_l', \beta_l, L_{0l}' \), while \( M_{0l, z>0.2} \) is kept fixed to the value found for the \( z < 0.2 \) LF), plus the power index \( p_M \) to account for the evolution of \( M_0 \), six duty cycle parameters, and one amplitude for the cirrus contamination, \( C_{250} \). When model fitting to the measured angular power spectrum at 250 \( \mu \)m, we calculate the total theoretical \( C_{\ell} \) as the sum of the \( C_{\ell} \) for the low-\( z \) HOD found in the previous fit and the \( C_{\ell} \) calculated at \( z > 0.2 \). This allows us to treat two types of galaxy populations that are contributing to the Herschel galaxy population, the low-\( z \) \((z < 0.1)\) dust in late-type galaxies and the dusty spheroidal galaxies at high redshifts (Lagache et al. 2003), and to account for a possible redshift evolution of the other \( L–M \) relation parameters (\( L_0, \alpha_l, \beta_l \)). Here we consider galaxies brighter than \( L > 5 \times 10^9 L_\odot \) for the low-redshift model, while we use \( L > 10^9 L_\odot \) to model-fit the high-redshift data. These values are consistent with the flux cut of the galaxy samples considered.

In order to account for the uncertainty in the exact value of \( L_{\text{min}} \), we have verified that an order-of-magnitude change in the value of \( L_{\text{min}} \) leads to changes in the power spectra of the order of 5%–6%, which is comparable to the 1\( \sigma \) error bars of the data. We find that the exact value of \( L_{\text{min}} \), within an order of magnitude, does not change the results considerably.

To model-fit the data, we implement an MCMC analysis using a modified version of the cosmicMC Lewis & Bridle (2002) package. The results for the low-\( z \) \( z < 0.2 \) 250 \( \mu \)m LF data are shown in Figure 1 and in Table 1, where we show and tabulate the best fit to the LF data and the best-fit values for the CLF parameters involved with the LF description, respectively. In Figure 1, we show the HOD calculated for the best-fit values of the parameters and its uncertainties.

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Table 1

| Parameter | Value |
|-----------|-------|
| \( \alpha_l \) | 0.22 ± 0.10 |
| \( \beta_l \) | 0.70 ± 0.05 |
| \( \log(M_{0l}/M_\odot) \) | 11.5 ± 1.7 |
| \( \log(L_{0l}/L_\odot) \) | 9.6 ± 2.4 |
| \( \eta_{\text{DC}}(0 < z < 0.2) \) | 0.54 ± 0.26 |

Figure 1 shows the model-fit to the data and the best-fit values for the CLF parameters involved with the LF description, respectively. In Figure 1, we show the HOD calculated for the best-fit values of the parameters and its uncertainties.

The best-fit model to the angular power spectrum data and high-\( z \) LFs is shown in Figures 2 and 3. In Table 2 we tabulate the best-fit parameter values (where the prime is used to distinguish the parameters for the high-\( z \) luminosity–mass relation from those for the low-\( z \) case), and in Figure 4 we show the probability contours for the luminosity–mass relation parameters.
However, it should be noted that in this work we are not fitting at $z$ mass of the standard halo model and is in agreement with $\log(z) = (2011)$ may not be appropriate. Thus, a direct comparison of our work to Amblard et al. (2011) shows a sharp cutoff at a mass of about $\log(M_{\text{min}})$ assuming no scatter in the luminosity–mass relation. The HOD can be done through the effective halo mass scale:

$$M_{\text{eff}} = \int dM n_h(M) M N_f. \tag{22}$$

Integrating over our HODs, we find $\log(L_0/L_\odot) = 9.58 \pm 0.02$, which is comparable to the results of Shang et al. (2011). Nevertheless, again, as already noted in Shang et al. (2011), the difference was found in the cirrus contamination. The model attempted to model-fit high signal-to-noise power spectrum measurements using both a halo model and a power-law power spectrum for cirrus. The simple halo occupation number used in Amblard et al. (2011) is not able to make a distinction between the luminosity and mass of satellite galaxies. Moreover, in the current description, the shape of the luminosity–mass relation determines the strength of the one-halo term, while in the standard halo model, the strength of the one-halo term is mainly determined by the slope of the halo occupation number of satellite galaxies. As the one-halo term is clearly detected in the Herschel CFIRB power spectrum, the previous results were biased by an incorrect model that attempted to model-fit high signal-to-noise power spectrum measurements. We are also finding an amplitude for the cirrus contamination that is smaller than 1: $C_{250} = 0.78 \pm 0.16$. A reduced cirrus contamination requires a reduced relative amplitude between the one-halo and two-halo terms that can be achieved with a lower slope for the satellite contributions. We note also that the fit to the cirrus amplitude confirms that the previous analysis of the same clustering data in Amblard et al. (2011) overestimated the cirrus contribution as already has been found by the Planck Collaboration (2011), where a factor $\sim 2$ of difference was found in the cirrus contamination. The model

![Figure 4. 68% and 95% confidence level contours for the parameters of the luminosity–mass relation $L_0^\alpha_0$ (left) and $L_0^\alpha_s$ (right).](image)

| Table 2 Best-fit Parameter Values and Their 1σ Uncertainties from the Combination of Angular CFIRB Power Spectrum at 250 $\mu$m and High-$z$ Luminosity Function Data |
|---|
| $\alpha_0'$ | 0.57 ± 0.03 |
| $\beta_0'$ | 0.19 ± 0.02 |
| $\log(L_0^\alpha/L_\odot)$ | 9.58 ± 0.02 |
| $C_{250}$ | 0.78 ± 0.16 |
| $\eta_{\text{DC}} (0.2 < z < 0.4)$ | 0.43 ± 0.07 |
| $\eta_{\text{DC}} (0.4 < z < 0.8)$ | 0.30 ± 0.04 |
| $\eta_{\text{DC}} (1.2 < z < 1.6)$ | 0.16 ± 0.01 |
| $\eta_{\text{DC}} (1.6 < z < 2.0)$ | 0.19 ± 0.01 |
| $\eta_{\text{DC}} (2.0 < z < 2.4)$ | 0.33 ± 0.01 |
| $\eta_{\text{DC}} (2.4 < z < 4.0)$ | 0.31 ± 0.02 |
| $\rho_{\text{DM}}$ | -4.32 ± 0.09 |

These results show that the model is able to fit the data even assuming no scatter in the luminosity–mass relation. The HOD shows a sharp cutoff at a mass of about $\log(M_{\text{min}}/M_\odot) \approx 10.8$ at $z = 0$. This quantity could be compared to the threshold mass of the standard halo model and is in agreement with the results of Amblard et al. (2011), where it was found that $\log(M_{\text{min}}/M_\odot) \approx 11.5$ with a simple HOD for the dusty galaxies. However, it should be noted that in this work we are not fitting directly the value of $M_{\text{min}}$ as it is not a free parameter in our model. Thus, a direct comparison of our work to Amblard et al. (2011) may not be appropriate.

Both the values mentioned above are different from the recent results of Shang et al. (2011), where the authors used an improved version of the halo model including a luminosity–mass relation to analyze the Planck-based CFIRB anisotropy power spectrum (Planck Collaboration 2011). They found that the most efficient halo mass scale for star formation is $M_{\text{eff}} \approx 10^{12.65} M_\odot$, which is closer to the typical value of optical galaxies in the standard halo model (Cooray & Sheth 2002; Abazajian et al. 2005). Nevertheless, again, as already noted in Shang et al. (2011), the model used there is different from the one used in Amblard et al. (2011) (and from the one used in this paper), and a direct comparison between $M_{\text{eff}}$ and $M_{\text{min}}$ may not be accurate. A proper comparison of our model to the results of Shang et al. (2011) can be done through the effective halo mass scale:

$$M_{\text{eff}} = \int dM n_h(M) M N_f. \tag{22}$$

Integrating over our HODs, we find $\log(L_0^\alpha_{\text{eff}}) = 12.63$ at $z = 0$, which is comparable to the results of Shang et al. (2011). It is also comparable to results for optical galaxies (Cooray & Sheth 2002; Abazajian et al. 2005).
used in this work is hence able to alleviate the tension between Planck and Herschel analysis.

In terms of the duty cycle parameters, at \( z < 0.2 \), where the constraint came only from the LF data, we found a weak constraint on the duty cycle, which is \( \eta_{ DC} = 0.54 \pm 0.48 \) at 95% confidence level. The amplitude of the LF is in fact affected by both the duty cycle and other parameters of the luminosity mass relation, in particular \( L_0 \) and \( M_0 \). Thus, in the absence of other constraints, the duty cycle cannot be measured efficiently. On the other hand, the parameters of the \( L-M \) relation also determine the HOD and the relative amplitude of one-halo and two-halo terms. Combining clustering measurements and LF data can hence strongly improve the constraints on the duty cycle. Also, the \( z < 0.2 \) LF is better determined in narrow, deeper surveys compared to the case of the \( z < 0.2 \) LF. All this results in a determination of high-\( z \) duty cycle parameters with relatively small uncertainties. We have found that the duty cycle generally decreases with redshift until \( z \approx 1 \) and slowly increases again for higher \( z \) (see Table 2 and Figure 5). The values are in the range \( \eta_{ DC} \approx 0.16-0.4 \) when \( 0.2 < z < 0.4 \).

In Shang et al. (2011), the authors have excluded very low duty cycle values (\( \eta_{ DC} < 0.05 \)), but that the Planck power spectrum data favor duty cycles close to unity. Our results are in the middle between these two extreme cases. However, in Shang et al. (2011), the duty cycle parameter is estimated by comparing the shot noise predicted for a fixed \( \eta_{ DC} \) to the results of the empirical model of Bethermin et al. (2011), rather than fitting to the data. Moreover, the model used here differs in the description of the luminosity--mass relation and introduces a possible redshift evolution both for the duty cycle and for the 250 \( \mu \)m luminosity--halo mass relation. Interestingly, our constraints are much more similar to the results of Lee et al. (2009), where the model we are using here, with some differences in the \( L-M \) relation and its redshift dependence, was also used to analyze the UV LF and two-point correlation function data of star-forming galaxies in the range \( z = 4-6 \). In that work, Lee et al. (2009) used \( \eta_{ DC} \) as an input parameter rather than as a free parameter and found that extremely short (\( \eta_{ DC} < 0.1 \)) and extremely long (\( \eta_{ DC} > 0.7 \)) duty cycles are ruled out at the 90% confidence level. Our results also suggest a mid-range for \( \eta_{ DC} \). The agreement could imply that a large fraction of the UV-selected star-forming galaxy sample studied in Lee et al. (2009) could also be responsible for the CFIRB anisotropies. This could be directly tested via a cross-correlation between the two data sets, and such studies are expected in the near future given the Herschel imaging of some of the wide-area legacy fields.

In Section 3, we described the duty cycle in terms of the duration of the star formation \( t_{ SF} \) in the halos with respect to the time interval \( \Delta t \) covered by the survey. A long duty cycle \( \eta_{ DC} \approx 1 \) implies a star formation timescale that is \( t_{ SF} \gg \Delta t \), while small duty cycles with \( \eta_{ DC} \sim 0 \) correspond to the opposite case with \( t_{ SF} \ll \Delta t \). The central value with \( \eta_{ DC} \sim 0.5 \) implies \( t_{ SF} \approx \Delta t \). In terms of the physical time, once accounting for the time interval spanned by each redshift bin, the duty cycles listed in Table 2 correspond to a star formation phase lasting for \( t_{ SF} \approx 0.3-1.6 \) Gyr. Such a long star formation timescale is consistent with what has been suggested in Lapi et al. (2011) and the physical model of Granato et al. (2001, 2004). Such a long timescale rules out models where the CFIRB is dominated by gas-rich mergers with \( t_{ SF} \approx 10-100 \) Myr.

It is worth noticing that in this analysis we are assuming a duty cycle that is independent of mass. It could very well be that the duration of star formation depends on the halo mass. Given the large number of free parameters in the analysis, we are not able to characterize a possible mass or luminosity dependence of \( \eta_{ DC} \), but we regard this possibility as a future improvement to this model.

Our analysis suggests that the \( L-M \) relation has a redshift dependence, with \( M_0 \) that decreases for higher redshifts (see Equation (14)). Decreasing \( M_0 \) is equivalent to increasing the characteristic luminosity of the LF. The fit to the high-\( z \) LF data is shown in Figure 3. In particular, we find \( M_0 \propto (1+z)^{-3.2\pm0.9} \). Although a direct comparison is complicated because of the very different models used, we note that this result is similar to the evolution seen in LeFloc’h et al. (2005), where the characteristic luminosity has been found to have a redshift dependence \( \propto (1+z)^{0.25} \).

The total luminosity–mass relation calculated as

\[
L(M) = \bar{L}(M) + \int N(m|M)\bar{L}(m)dM
\]  

is shown in Figure 6. The shaded regions represent the 1\( \sigma \) uncertainty, and it can be seen that the data are able to constrain

Figure 5. Duty cycle \( \eta_{ DC} \) as a function of redshift. Over the redshift range of \( 1 < z < 4 \), \( \eta_{ DC} \approx 0.2-0.4 \).

Figure 6. 250 \( \mu \)m luminosity–halo mass relation and the 68% confidence level region at \( z = 0, 1, \) and 2.

(A color version of this figure is available in the online journal.)
the luminosity–mass relation with good precision even for the \( z < 0.2 \) case using only the low-redshift LF data. The luminosity–mass relations we are finding show a linear behavior. However, the LFs are steep at the low-faint luminosity end. This results in a tension when the observed turnover is attempted to be explained through the abundance matching approach in Bethermin et al. (2012). We consider this as a natural consequence of the fact that in this work we are attempting to fit simultaneously data sets in a large range of redshifts together with anisotropy power spectrum measurements. Moreover, we observe that there is no clear visible turnover in the data that we are fitting without imposing any prior or constraint on the faint end of the LFs. The faint-end description, both in data and in models, should be further improved.

In Figure 7 we show the emissivity corresponding to the best-fit model, calculated according to Equation (21) and compared to the emissivity of the parametric model of Bethermin et al. (2011; see also Penin et al. 2012). The extended tail at \( z > 3 \) is due to the constant and the fast increase of the LF with redshift. We have verified that using the emissivity of Bethermin et al. (2011) implies a few percent difference in the best-fit values of the CLF parameters in the model presented here, comparable to the 1\sigma error bars. Future analysis may require, however, a different redshift parameterization of the average luminosity–mass relation.

We show also the satellite fraction for the four high-redshift bins calculated by van de Bosch et al. (2007):

\[
f_{\text{sat}}(L) = \frac{1}{\Phi(L)} \int_{M'}^{\infty} dM P(L|M)n_T(M),
\]

where \( M' \) is the mass scale where there is one galaxy brighter than \( L \). The satellite fraction is an important test for galaxy formation models and to establish the properties of the galaxy–halo relation. We find that the fraction is about 22\%–25\% at \( L = 10^9 L_\odot \) and decreases quickly to less than 5\% at \( 10^{11} L_\odot \), while we do not find a significant redshift dependence. The decreasing behavior with mass is due to the fact that satellite galaxies at a given luminosity are located in more massive (and hence less numerous) halos with respect to central galaxies. This result for \( f_{\text{sat}} \) is also in agreement with van de Bosch et al. (2007), Cooray (2006b), and Coupon et al. (2011).

Finally, in Figure 8 we show the fraction of dust with respect to the critical density of the universe \( \rho_c \), calculated as

\[
\Omega_{\text{dust}} = \frac{1}{\rho_c} \int_{L_{\text{min}}} \phi(L) dL \frac{dL}{d\Omega(L, \mu) M_{\text{dust}}(L)},
\]

where \( M_{\text{dust}} \) is the dust mass corresponding to a given IR luminosity and we use Equation (4) in Fu et al. (2012). The results are compared to those in Figure 7 of Menard & Fukugita (2012), where \( \Omega_{\text{dust}} \) has been determined with reddening of metal-line absorbers. In Figure 8 we also show other estimates of the mass density of dust as summarized by Menard & Fukugita (2012) from Fukugita et al. (2004), Driver et al. (2007), Menard et al. (2010), and Fukugita (2011). We have combined the points from Menard et al. (2010) for the dust contributions of halos and those from Menard & Fukugita (2012) in a single set of data points, under the assumption that the amount of dust in halos hasn’t evolve significantly with redshift. We parameterize the opacity with a power law \( k_d \propto \nu^{\beta_d} \) with the power index in the range \( 1.5–2 \). The calculation requires the spectral energy distribution of dust, and we assume a thermal blackbody spectrum with dust temperature in the range \( T = 25–35 \, \text{K} \). We allow for a large range in dust temperature, taken as a uniform prior, to allow for the range of values seen in current data (Amblard et al. 2010). In Equation (25) we integrate over luminosities \( L_{\text{min}} > 10^9 L_\odot \). However, in this calculation the choice of \( L_{\text{min}} \) is less relevant, since the uncertainty on \( \Omega_{\text{dust}} \) is dominated by the large range of temperatures and spectral indices considered. The shaded region corresponds to the prediction for these parameter ranges using the best-fit LFs of Figure 3.

5. CONCLUSION

We have presented an analysis of the Herschel-SPIRE CFIRB power spectrum at 250 \( \mu \text{m} \) and the LFs up to \( z = 4 \). We use a CLF approach to model the far-IR bright galaxies. We have modeled the 250 \( \mu \text{m} \) LF and its evolution with redshift introducing a redshift-dependent duty cycle parameter. This description represents an improved version of the halo model that offers an advantage by accounting for the luminosity dependence of the satellite galaxies as a function of the halo.
mass. The underlying ingredient is the galaxy luminosity–halo mass relation.

We have found that current Herschel data are able to constrain the model despite the high number of free parameters. The results of our analysis indicate that the CFIRB is dominated by star-forming galaxies in an extended phase of star formation rather than bright starbursts that are fueled by gas-rich mergers. We found duty cycles corresponding to a dusty star formation phase lasting ∼0.3–1.6 Gyr, which is in agreement with previous analysis of star-forming UV-selected galaxies at high redshifts.

We have also found that the halo occupation number for satellite galaxies has a power-law slope that is about 0.98 over a redshift range 0 < z < 4. This solves the tension between previous analysis of the same Herschel power spectrum data and other determinations of the halo occupation number for galaxies in the literature. Finally, we have estimated the cosmic density of dust residing in the dusty, star-forming galaxies responsible for the CFIRB anisotropies to be Ω_{dust} ~ 3 × 10^{-3} to 2 × 10^{-5}.

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