SUBMILLIMETER GALAXY NUMBER COUNTS AND MAGNIFICATION BY GALAXY CLUSTERS

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Abstract

We present an analytical model which reproduces measured galaxy number counts from surveys in the wavelength range of 500 µm to 2 mm. The model involves a single high-redshift galaxy population with a Schechter luminosity function which has been gravitationally lensed by galaxy clusters in the mass range $10^{13}$ to $10^{15} M_\odot$. This simple model reproduces both the low flux and the high flux end of the number counts reported by the BLAST, SCUBA, AzTEC and the SPT surveys. In particular, our model accounts for the most luminous galaxies detected by SPT as the result of high magnifications by galaxy clusters (magnification factors of 10-30). This interpretation implies that submillimeter and millimeter surveys of this population may prove to be a useful addition to ongoing cluster detection surveys. The model also implies that the bulk of submillimeter galaxies detected at wavelengths larger than 500 µm lie at redshifts greater than 2.

Subject headings: galaxies: clusters — gravitational lensing — submillimeter: galaxies

1. INTRODUCTION

Over the last decade, submillimeter (submm) surveys have yielded significant advances in our understanding of the galaxy population responsible for the high-redshift component of the cosmic infrared background (CIB) (Fixsen et al. 1996; Smail et al. 1997; Hughes et al. 1998; Barger et al. 1998; Dwek et al. 1998; Fixsen et al. 1998; Greve et al. 2004; Pope et al. 2006; Coppin et al. 2006; Devlin et al. 2009). With typical far-infrared (FIR) luminosities $>10^{12} L_\odot$, submm galaxies are presumed to be the high-redshift counterparts to (ultra) luminous infrared galaxies (LIRGs, ULIRGs). The high luminosity of these galaxies is the result of star formation rates of 100–1000 $M_\odot$ yr$^{-1}$. Approximately half of these galaxies are located at $1.9<z<2.9$ (Chapman et al. 2005; Aretxaga et al. 2007), dominating the total star formation rate at this epoch (Pérez-González et al. 2006).

One way to express the results of submm surveys is through number counts of galaxies as a function of flux for each observed wavelength. The shape of these counts has been interpreted as arising from different populations of galaxies whose characteristics evolve over cosmic time (Lagache et al. 2003, 2004; Pearson & Khan 2003; Le Borgne et al. 2009). These empirical models have successfully reproduced the counts. However, they may be masking a simpler explanation for the departure of the counts from a Schechter distribution at the high-flux end: magnification due to high redshift galaxy clusters and groups (e.g. Blain 1996; Perrotta et al. 2002; Negrello et al. 2004).

Millimeter wavelength surveys have also aimed at detecting galaxy clusters via the Sunyaev Zel’dovich (SZ) effect (Hincks et al. 2008; Carlstrom et al. 2003). The first results, including CMB power spectra and cluster catalogs, have been released recently (Fowler et al. 2010; Staniszewski et al. 2009; Vanderlinde et al. 2010). The number of detected clusters remains relatively low, primarily due to the low value of $\sigma_8$. However, other effects could be reducing the sensitivity of the surveys (e.g. Lima et al. 2009, 2010).

The South Pole Telescope (SPT) has measured number counts of dusty galaxies at wavelengths $\lambda=1.4$ mm and 2.0 mm over an area of 87 deg$^2$ (Vieira et al. 2009). The observed numbers at the bright end are higher than expected: these galaxies are either at high redshifts and intrinsically exceptionally luminous, or have been magnified by gravitational lensing, or are simply at much lower redshifts than the bulk of the population of submm galaxies. The latter possibility is disfavored by the lack of detected counterparts in other surveys that probed the low redshift population (Vieira et al. 2009). The possibility that these galaxies are at high redshifts and intrinsically bright would require them to be far more luminous than an underlying Schechter-like luminosity function would permit. Thus the favored explanation is that they have typical luminosities for high-$z$ galaxies, but have been magnified by foreground galaxies or clusters. Lensing of high-redshift background submm galaxies has been observed (Smail et al. 1997, 2002), and more recently in the Bullet Cluster with the 1.1 mm AzTEC receiver on the Atacama Submillimeter Telescope Experiment as well as with the Balloon-borne Large Aperture Submillimeter Telescope - BLAST (Wilson et al. 2008; Rex et al. 2009; Gonzalez et al. 2009). In this Letter, we explore the possibility that the existing observed galaxy number counts over a wide range of wavelengths can be reproduced by a single population of galaxies at high-redshift. Foreground galaxy groups and clusters gravitationally lenses the background submm population (Lima et al. 2009) and leads to significant enhancements of the high-flux end to the galaxy counts. In §2 we describe the lensing magnification formalism, which we then apply to a high-$z$ galaxy population and present results in §3. We discuss implications for high-$z$ galaxies and the cluster searches in §4.

Throughout, we use a fiducial cosmology for a flat universe with parameter values based on the results of the Wilkinson Microwave Anisotropy Probe fifth year data
where $\mu$ is the lensing magnification and $P(\mu)$ is its probability for a given galaxy population at redshift $z_s$. Conditional probabilities quantify the effects of different magnification ranges on the observed flux density $S_{\text{obs}}$. The integrand of Eq. 2 defines the probability $P(\mu|S_{\text{obs}})$

$$P(\mu|S_{\text{obs}}) = \left(\frac{dn_{\text{obs}}(S_{\text{obs}})}{dS_{\text{obs}}}ight)^{-1} \frac{P(\mu)}{\mu} \frac{dn}{dS} \left(\frac{S_{\text{obs}}}{\mu}\right),$$

which can be interpreted as the relative contribution of a given $\mu$ to the total $dn_{\text{obs}}/dS_{\text{obs}}$ at $S_{\text{obs}}$ [Paciga et al. 2008]. Similarly $P(\mu_{\text{min}}|S_{\text{obs}})$ measures the integrated contribution from all $\mu > \mu_{\text{min}}$. The mean magnification at a given $S_{\text{obs}}$ is defined as

$$\langle \mu \rangle(S_{\text{obs}}) = \int_0^\infty d\mu \mu P(\mu|S_{\text{obs}}).$$

The distribution $P(\mu)$ can be estimated either by ray-tracing on N-body simulations (e.g. Hilbert et al. 2007) or by semi-analytical methods (e.g. Perrotta et al. 2002; Lima et al. 2009), integrating halo contributions on the line of sight up to the source redshift

$$P(>\mu) = \int_0^{z_s} dz \frac{D_A^2(z_i)}{H(z_i)} \int_{M_{\text{min}}}^{\infty} d\ln M \frac{dn(z_i, M)}{d\ln M} \Delta \Omega_\mu,$$

where $D_A$ is the angular diameter distance, $H$ is the Hubble parameter, $dn/d\ln M$ is the halo mass-function and $\Delta \Omega_\mu = \Delta \Omega_\mu(z_s, z, M)$ is the cross-section for magnifications larger than $\mu$ produced by halos of mass $M$ at redshift $z_i$ on sources at redshift $z_s$. The integrand

$$\frac{d^2 P(>\mu)}{d\ln M d\ln z_i} = \frac{D_A^2(z_i)}{H(z_i)} \frac{dn(z_i, M)}{d\ln M}$$

gives the range of halo masses and redshifts contributing most to the probability of a specified minimum magnification $\mu$.

In summary, Eqs. 2 and 5 give the total effect on the counts, Eq. 3 indicates which magnifications contribute most to the given $S_{\text{obs}}$ and Eq. 4 tells us which halo masses and redshifts contribute to a given magnification.

We use this halo-model $P(\mu)$ and correct it for a number of effects. First, as described in Lima et al. (2009), we match our $P(\mu)$ at large magnifications to that of ray-tracing in dark matter simulations [Hilbert et al. 2007] by tuning the ellipticity of our halos. Next, we account for the effect of luminous matter, which can lead to higher densities via gas cooling, using the simulation results of Hilbert et al. (2008). We also correct for the combination of finite source size and multiple image effects. Magnification effects, especially for large magnifications, are sensitive to the value of $\sigma_S$ since it affects the abundance of cluster halos. In the next section we discuss how we account for the uncertainties in our model by giving a range for our predictions.

Our analytical calculation of $P(\mu)$ has some advantages over the approach of numerical simulations (we can easily study changes in source redshift, $\sigma_S$ and the contribution from different halo masses and redshift), but it also has some limitations. We only use the one-halo term, which is accurate at the high magnifications relevant for the effects considered here but overestimates the lensing.

**2. NUMBER COUNTS WITH LENSING MAGNIFICATION**

In recent papers [Lima et al. 2009; Jain & Lima 2010] we have presented a halo model for calculating the effects of lensing magnification by galaxy groups and clusters. Here we specialize to the case of steep galaxy counts at high redshifts, where lensing effects are quite dramatic. We assume a Schechter function (Schechter 1976) for the intrinsic number density distribution of a population of galaxies

$$\frac{dn}{dS} = n^* \left(\frac{S}{S^*}\right)^{\alpha} e^{-S/S^*},$$

where $n^*$, $S^*$ and $\alpha$ are free parameters. Due to lensing magnification by intervening halos, the intrinsic $dn/dS$ is changed to its observed counterpart as

$$\frac{dn_{\text{obs}}(S_{\text{obs}})}{dS_{\text{obs}}} = \int d\mu \frac{P(\mu)}{\mu} \frac{dn}{dS} \left(\frac{S_{\text{obs}}}{\mu}\right),$$

where $\mu$ is the lensing magnification and $P(\mu)$ is its probability for a given galaxy population at redshift $z_s$.
different wavelengths are given in Table 1 and are consistent with theoretical expectations. Counters. Note that no similar removal has been applied to the BLAST data, which includes both high and low redshift galaxies.

\[ \alpha = -1.0 \text{ and } n^* = 5 \times 10^3 \text{ deg}^{-2} \]

Table 1

<table>
<thead>
<tr>
<th>Survey</th>
<th>( \lambda (\mu m) )</th>
<th>( S^* (mJy) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLAST</td>
<td>500</td>
<td>11.00</td>
</tr>
<tr>
<td>SCUBA</td>
<td>850</td>
<td>3.26</td>
</tr>
<tr>
<td>AzTEC</td>
<td>1100</td>
<td>1.28</td>
</tr>
<tr>
<td>SPT</td>
<td>1400</td>
<td>1.00</td>
</tr>
<tr>
<td>SPT</td>
<td>2000</td>
<td>0.35</td>
</tr>
</tbody>
</table>

In Fig. 1 we illustrate the lensing effect on an intrinsic Schechter function describing galaxies at \( z_s = 3.0 \) and different wavelengths. Dashed lines indicate the intrinsic Schechter functions (with different \( S^* \) values) and the shaded regions display the range of lensing predictions, as described in the text. Also shown are observed counts for BLAST at \( \lambda = 500 \mu m \), SCUBA at \( \lambda = 850 \mu m \) and SPT at both \( \lambda = 1.4 \) mm and 2.0 mm. The SPT counts are for dusty galaxies, after removal of galaxies with synchrotron emission and galaxies with IRAS counterparts. Note that no similar removal has been applied to the BLAST data, which includes both high and low redshift galaxies.

(Right) : Unified scaled curves showing \(dn/dS\) and the various data points. The only parameter used in the scaling is \( S^* \); its values at the different wavelengths are given in Table 1 and are consistent with theoretical expectations.

Figure 2. (Left) : Intrinsic and lensed \(dn/dS\) for a Schechter function describing galaxies at \( z_s = 3.0 \) and different wavelengths. Dashed lines indicate the intrinsic Schechter functions (with different \( S^* \) values) and the shaded regions display the range of lensing predictions, as described in the text. Also shown are observed counts for BLAST at \( \lambda = 500 \mu m \), SCUBA at \( \lambda = 850 \mu m \) and SPT at both \( \lambda = 1.4 \) mm and 2.0 mm. The SPT counts are for dusty galaxies, after removal of galaxies with synchrotron emission and galaxies with IRAS counterparts. Note that no similar removal has been applied to the BLAST data, which includes both high and low redshift galaxies.

(Right) : Unified scaled curves showing \(dn/dS\) and the various data points. The only parameter used in the scaling is \( S^* \); its values at the different wavelengths are given in Table 1 and are consistent with theoretical expectations.

3. RESULTS

In Fig. 1 we illustrate the lensing effect on an intrinsic Schechter function distribution given by Eq. 1 for sources at different redshifts. In all results presented here, we fix \( \alpha = -1.0 \) and \( n^* = 5 \times 10^3 \text{ deg}^{-2} \). Changing to \( \alpha = -1.5 \) does not have a significant effect – while it matches the faint end behavior of \(dn/dS\) for the model of Lagache et al. (2004), we preferred to use \( \alpha = -1.0 \) since this fits better the number counts at shorter wavelengths. With these parameter values, our counts are lower than the model of Lagache et al. (2004) at all \( S \), which also ensures that the total flux does not exceed the CIB (Dwek et al. 1998; Fixsen et al. 1998).

Fig. 2 illustrates our main results: we show predicted number counts that include lensing (gray bands), assuming galaxies at \( z_s = 3.0 \), along with measured number counts from submm surveys at different wavelengths. As indicated in the panels, these are: BLAST at \( \lambda = 500 \mu m \) (Devlin et al. 2009), SCUBA at \( \lambda = 850 \mu m \) (Coppin et al. 2006), AzTEC at 1.1 mm (Austermann et al. 2010) and SPT dusty submm galaxies at \( \lambda = 1.4 \) mm and 2.0 mm (Vieira et al. 2009). In all our results, the SPT number counts correspond to those of Vieira et al. (2009), after removing both synchrotron emission galaxies as well as low-redshift galaxies that have matches with galaxies in the Infrared Astronomy Satellite survey (IRAS, Moshir et al. 1992; Fisher et al. 1993, Oliver et al. 1999). Predictions are shown by bands rather than curves to reflect the uncertainties in the model as discussed below. The intrinsic luminosity function is the Schechter function described above. All the data sets can be fit by changing the single parameter \( S^* \) once lensing magnification is included. This remarkable result implies that, within the measurement and theoretical uncertainties, a single high-z population of galaxies is sufficient to describe all the observations. The high flux measurements of BLAST and SPT are fit by highly magnified galaxies – if these counts were dominated by a population of a different galaxy type, it would be a co-
incidence that their relative counts fit the same scaling with wavelength as the fainter (“normal”) population.

The lower bound for the predictions in Fig. 2 uses $\sigma_S = 0.77$ while the upper bound uses $\sigma_S = 0.83$ – these reflect the uncertainties in the WMAP results as discussed above. The enhancement due to baryons is factored into these predictions following [Hilbert et al. (2008)], though it is likely to be an underestimate of baryonic effects as discussed above in Section 2. The effect of source sizes and multiple imaging is uncertain; we simply assume that due to the finite source size the effective magnification is reduced by 50% to 25% (for the lower and upper bounds respectively).

The right panel of Fig. 2 shows all points rescaled by plotting
\[
\frac{d\tilde{n}}{dS} = S^\alpha e^{-S},
\]
where $\tilde{n} = n/n_\ast$ and $S = S/S_\ast$. In Table 1 we show values of $S_\ast$ used for each wavelength. We compared the frequency scaling of $S_\ast$ with that of a typical Spectral Energy Distribution (SED) of submm galaxies $\text{SED}(\lambda) \propto \epsilon(\lambda)B(T,\lambda)$, with emissivity $\epsilon(\lambda) = 1 - \exp(-\lambda_0/\lambda)^\beta$ and blackbody spectrum $B(T,\lambda)$ at temperature $T$. The values of $S_\ast$ are consistent with $\beta = 1 - 2$ and $T = 20 - 40 K$, as expected for high redshift submm galaxies.

The fit to the BLAST counts at $\lambda = 500$, 350 and 250 $\mu$m falls further below the high flux measurement at shorter wavelengths, suggesting the need for a lower redshift population. Indeed, Eales et al. (2009) have identified the radio and 24 $\mu$m counterparts of the bright BLAST sources. At 250 $\mu$m almost all of the bright sources are identified as being at redshifts lower than 1. One third to one half of the sources in the highest flux bin at 500 $\mu$m come from sources with $z < 1$. Removing these would lower the corresponding point in Fig. 2 in agreement with the model. The remaining sources at 500 $\mu$m (and less than a tenth of the sources at 250 $\mu$m) are likely the result of lensing. Similar results should be expected with the upcoming release of the large-area Herschel surveys.

Since the lensed distributions at $z_s = 3.0$ are consistent with SPT data points at both wavelengths, we study the range of magnifications and halo masses that would be contributing most in this case. As we consider larger values of $S_{\text{obs}}$, in particular $S_{\text{obs}}/S_\ast \gtrsim 10$, the observed sources come from intrinsically low flux sources which have been magnified significantly. Fig. 4 shows $P(\mu_{\text{min}}|S_{\text{obs}})$ and $\langle \mu \rangle$ as a function of $S_{\text{obs}}$ for SPT ($\lambda = 1.4$ mm) and indicates magnifications that contribute most at each $S_{\text{obs}}$. For instance, for $S_{\text{obs}} = 20 - 40$ mJy, the right panel shows that $\langle \mu \rangle \sim 20 - 30$. Another way to see this is via $P(\mu_{\text{min}}|S_{\text{obs}})$ (left panel), which integrates out the effects above a certain $\mu_{\text{min}}$, and shows that for $S_{\text{obs}} = 20 - 40$ mJy, we have $P(\mu_{\text{min}}|S_{\text{obs}}) > 0.5$ for $\mu_{\text{min}} \sim 10 - 20$.

These results imply that magnifications of $10 - 30$ are necessary to explain the boost in $dn/dS$ at $S_{\text{obs}} \sim 10 - 40$ mJy, if it is due to lensing of an intrinsic Schechter distribution. Note that due to the finite size of submm galaxies, their magnifications must have a cutoff, which is difficult to estimate, but may be in the range $\mu \sim 10 - 40$ (Perrotta et al. 2002). However, there is still substantial uncertainty in these estimates, since galaxies have been measured with estimated magnifications of at least $\sim 45$ (Paciga et al. 2008; Kneib et al. 2004).

In Fig. 4 we show $d^2P/d\ln Mdz_0$ as a function of halo mass for different values of $\mu_{\text{min}}$ and $z_0$. This indicates that halo masses above $10^{13} h^{-1} M_\odot$ contribute significantly to magnifications of $10 - 30$, with most of the contribution coming from $\sim 10^{14} h^{-1} M_\odot$. Note that this does not include baryonic effects, which boost the con-
We find that the high flux SPT number counts can be explained by highly magnified galaxies from this high-
z population to explain the high flux measurements. Such a population has been invoked in theoretical models
(Lagache et al. 2003) and suggested in the recent measurements of Vieira et al. (2009). Indeed, adding a signifi-

cant fraction of a second population could cause the predictions to exceed the measured counts once magni-

cation effects for the high-z population are included. It would also be difficult to explain how the scaling with

wavelength of the high flux number counts is the same as the lower flux counts if they came from different galaxy

populations. Since lensing does not depend on frequency, our model naturally follows this common scaling.

Current SZ surveys with sensitivities of $3 \sim 7 \times 10^{14}h^{-1}M_\odot$ cannot detect most halos that produce this

lensing contribution. Conversely, looking for extremely bright objects in millimeter and submillimeter wave-

lengths can be an efficient way to search for high-z halos of masses $M \sim 10^{14}h^{-1}M_\odot$. The number of halos

can be found in this way is only a small fraction of all halos within a given mass range. Follow up ob-

servations with optical telescopes should be able to confirm cluster candidates up to $z \sim 1$. These clusters and

groups host Brightest Cluster Galaxies with luminosities $L \sim 10^{11} - 10^{12}L_\odot$, based on the low-z results of

Johnston et al. (2007) from the Sloan Digital Sky Survey. Multi-band optical imaging with limiting magnitude of

$23 - 24$ (for the $r$ band) would enable identification of these groups and clusters. Conversely, targeted observa-

tions of the high magnification regions of known strong lensing clusters could provide detections of faint submm

galaxies (which would lie below the detection threshold without the magnification boost). Similar to the use of

clusters as gravitational telescopes in optical imaging, this may also help resolve submm galaxies. Planned ob-

servations with AzTEC and the Large Millimeter Telescope have considered such an approach (David Hughes, private communication).

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