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Modeling the evolution of infrared galaxies with a backward evolution model

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We present a new backwards evolution model. This model reproduces the statistical properties of the infrared galaxies among which the number counts between 15 microns and 1.1 mm, the luminosity functions, and the redshift distributions.
This model uses an evolution in density and luminosity of the luminosity function parametrized by broken power-laws with two breaks at redshift 0.9 and 2, and contains the two populations of the Lagache et al. (2004) model: normal and starburst galaxies. We also take into account the effect of the strong lensing of high-redshift sub-millimeter galaxies. It has 13 free parameters and 8 additional calibration parameters. We fit the parameters to the IRAS, Spitzer, Herschel and AzTEC measurements with a Monte-Carlo Markov chain. Our model adjusted on deep counts at key wavelengths reproduces well recent very discriminating observations like Oliver et al. (2010) *Herschel* number counts and the Jauzac et al. (2010) measured redshift distribution of the CIB.
We discuss the contribution to the cosmic infrared background (CIB) and to the infrared luminosity density of the different populations included in the model. We also estimate the effect of the strong lensing on the number counts, and discuss the recent discovery by the South Pole Telescope (SPT) of a very bright population lying at high-redshift.

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1. Introduction

The extragalactic background light (EBL) is the relic emission due to galaxy formation and evolution (stars, dust and accretion processes) since the recombination. The infrared ($8\ \mu m < \lambda < 1000\ \mu m$) part of this emission called cosmic infrared background (CIB) was detected for the first time in 1996 [1] and contains about half of the energy of the EBL [2]. Nevertheless, in the local universe, the optical/UV emissions are 3 times larger than infrared/sub-millimeter ones [3]. This pseudo-paradox is explained by a strong evolution of the properties of the infrared galaxies which increase the IR output.

The backwards evolution models [4, 5, 6, 7] use an evolution the luminosity function (LF) of the galaxies to reproduce empirically the galaxy counts, and other constraints. These models make only a description of the evolution and contain little physics. The parameters of these models were tuned manually to fit observational constraints. [8] used another approach and performed a non-parametric inversion of the counts to determine the LF. Nevertheless, this approach is complex, uses only one population of galaxy, and does not manage to reproduce the 160 μm number counts.

BLAST [9] and SPIRE [10] performed recently new observations in the sub-mm at 250, 350 and 500 μm. In their current version, most of the models fail to reproduce the number counts measured at these wavelengths [11, 12, 13, 14]. The Valiante et al. model [7] gives the best results, simulating the temperature scatter and the heterogeneity of the populations of active galactic nuclei (AGN), but this model strongly disagrees with the measurement of the redshift distribution of the CIB [15].

The discovery of very bright high-redshift dusty galaxies with SPT [16] suggests that the contribution of high-redshift galaxies strongly lensed by dark matter halos of massive low-redshift galaxies on the bright counts is non negligible. Five lensed sub-millimeter galaxies (SMGs) were identified in the Herschel ATLAS survey [17]. Few new model [18, 19, 20] also adress the effect of lensing.

We present a new simple and parametric model [21], which reproduces the latest observational constraints without using AGNs and/or temperature scatter. The parameters of this model (13 free parameters and 8 calibration parameters) were fitted from a large set of recent observations using a Monte Carlo Markov Chain (MCMC) method, allowing to study degeneracies between the parameters. This model also includes the effects of the strong lensing on the observations.

2. Brief Description of our parametric model

In our model, we assume that the luminosity(LF) is a classical double exponential function [22]

$$\Phi(L_{IR}) = \Phi^\star \times \big(\frac{L_{IR}}{L^\star}\big)^{1-\alpha} \times exp\big[-\frac{1}{2\sigma^2} log_{10}^2 (1+\frac{L_{IR}}{L^\star})\big)\big] \tag{2.1}$$

where $\Phi(L_{IR})$ is the number of sources per logarithm of luminosity and per comoving volume unit for an infrared bolometric luminosity L_{IR}. $\Phi_\star$ is the normalization constant characterizing the density of sources. $L_\star$ is the characteristic luminosity at the break. α drives the faint-end slope and σ the bright-end behavior. We assume a continuous evolution in luminosity and in density of the luminosity function with the redshift of the form $L^\star \propto (1+z)^{r_L}$ and $\Phi^\star \propto (1+z)^{r_\Phi}$ where r_L and

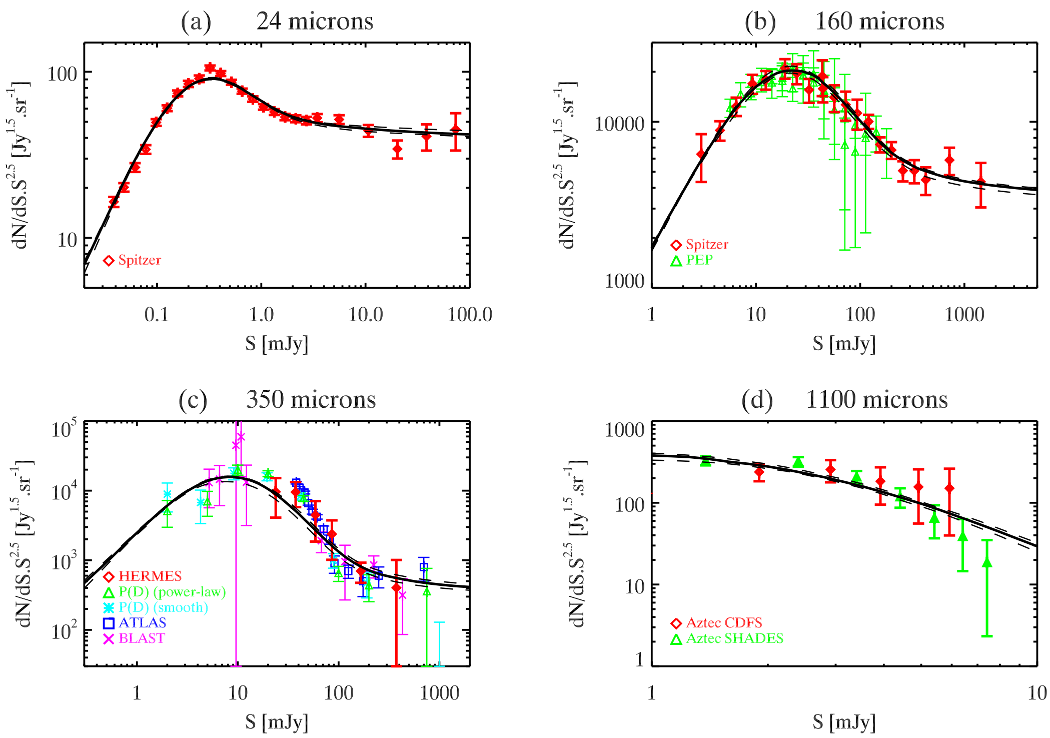

Figure 1: Differential extragalactic number counts used for the fit, here at 24 μm (a), 160 μm (b), 350 μm (c) and 1.1 mm (d). The fitted points are thicker. *Black solid line*: our best-fit model. *Black dashed line*: 1-σ range of the model. (a) to (b): *Red diamonds*: *Spitzer* legacy number counts [23]. (b): *Green triangles*: *Herschel*/PEP number counts. (c): *Red diamonds*: *Herschel*/Hermes number counts [24, 14]. *Green triangles*: *Herschel*/Hermes P(D) analysis [25]. *Herschel*/ATLAS number counts [13]. *Purple cross*: BLAST number counts [12]. (d): *Green triangles*: AzTEC number counts in the CDFS field [26]. *Green triangles*: AzTEC number counts in the SHADES field [27].

r_ϕ are coefficients driving the evolution in luminosity and density, respectively. We authorize their value to change at some specific redshifts. A first break near 0.9 is a free parameter and a second break is fixed at z=2.

We use the Lagache et al. SED (Spectral Energy Distribution) library [4]. This library contains two populations: a starburst one and a normal one. The normal galaxies are dominant at low luminosity and the starburst at high luminosity.

The lensing of high-redshift galaxies uses a simple strong lensing model, assuming that the dark matter halos are singular isothermal spheres [28, 29]. The observed number counts taking into account the lensing $(dN/dS_\nu/d\Omega)_{lensed}$ are computed from initial counts $dS_\nu/dz/d\Omega$ with

$$\left(\frac{dN}{dS_\nu d\Omega}\right)_{lensed}(S_\nu) = \int_0^\infty \int_{\mu_{min}}^{\mu_{max}} \frac{dP}{d\mu}(z) \frac{1}{\mu} \frac{dN}{dS_\nu dz d\Omega}\left(\frac{S_\nu}{\mu}, z\right) d\mu \, dz. \quad (2.2)$$

(μ is the magnification and dP/dμ is the probability density of magnification for a source at a z).

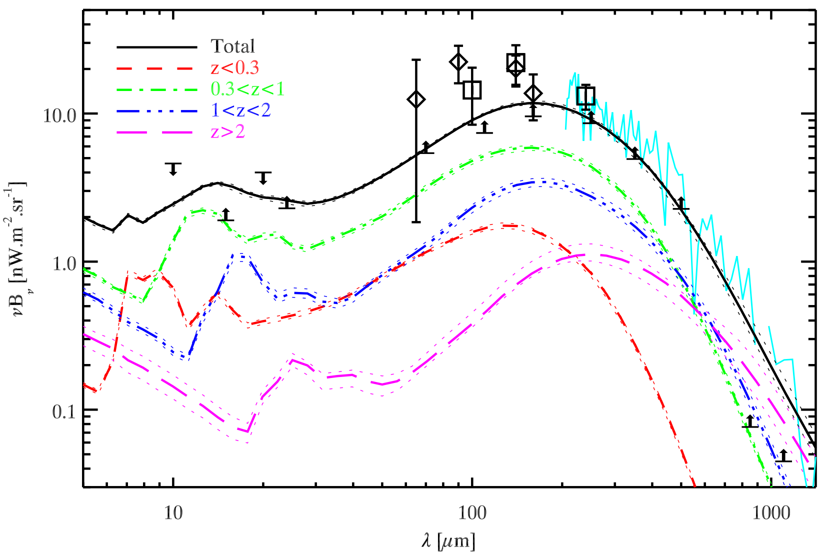

Figure 2: Contribution to the CIB per redshift slice. *Black solid line*: CIB spectrum predicted by the model. *Red short-dashed line*: Contribution of the galaxies between z=0 and 0.3. *Green dot-dash line*: Same thing between z=0.3 and 1. *Blue three dot-dash line*: same thing between z=1 and 2. *Purple long-dashed line*: Contribution of the galaxies at redshift larger than 2. *Black arrows*: Lower limits coming from the number counts at 15 μm [30] and 24 μm [23] and the stacking analysis at 70 μm [23], 100 μm, 160 μm [24], 250 μm, 350 μm, 500 μm [31], 850 μm [32] and 1.1 mm [26] and upper limits coming from absorption of the TeV photons of [33] at 20 μm and [34] between 5 μm and 15 μm. *Black diamonds*: absolute measurements with Akari [35] . *Black square*: absolute measurements with DIRBE/WHAM [36]. *Cyan line*: FIRAS measurement [36].

3. Fitting the parameters of the model

We have chosen to determine the free parameters of the model fitting the following data:

- number counts: *Spitzer* MIPS counts at 24, 70 and 160 μm [23], *Herschel* SPIRE counts at 250, 350 and 500 μm [14], AzTEC counts at 1.1 mm [27, 26],
- monochromatic luminosity functions: IRAS local luminosity function at 60 μm [22], *Spitzer* local luminosity function at 24 μm [37], *Spitzer* luminosity function at 15 μm at z=0.6 [37], *Spitzer* luminosity function at 12 μm at z=1 [37], *Spitzer* luminosity function at 8 μm at z=2 [38].
- FIRAS CIB spectrum between 200 μm and 2 mm[39].

We used a Monte Carlo Markov chain (MCMC) Metropolis-Hastings algorithm [40, 41] to fit our model to the observations. Our final best-fit model have a χ^2 of 177 for 113 degrees of freedom (see Fig. 1).

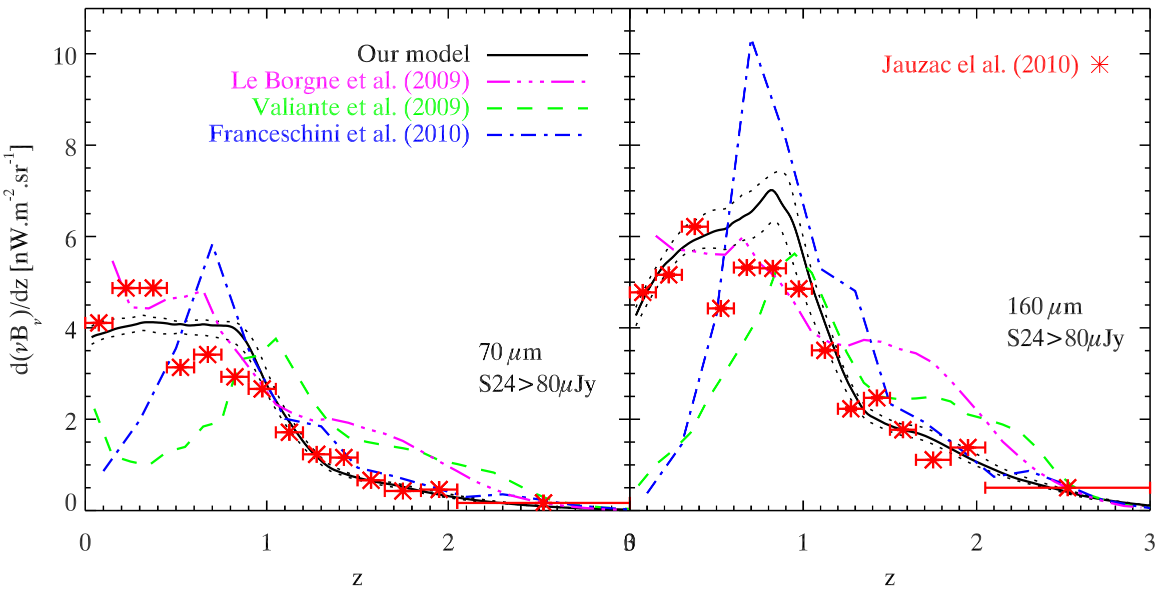

Figure 3: Differential contribution of the $S_{24} > 80$ μJy sources to the CIB as a function of the redshift at 70 μm (left panel) and 160 μm (right panel). *Red asterisks*: measurement by stacking in the COSMOS field [15]. *Black solid line*: Our model (1-σ limit in *black dotted line*). *Purple three dot-dashed line*: [8]. *Green dashed line*: [7]. *Blue dot-dashed line*: [5].

4. Results

Our model reproduces the redshift distributions of the infrared sources for different selections in the mid-IR and in the sub-mm, the contribution of the 24 μm sources to the CIB as a function of redshift, the Poissonnian fluctuations of the CIB and the BLAST pixel histograms.

Our model predicts a strong evolution in luminosity of the LF up to z=2 and a strong decrease in density from z=1 to z=2. We predict that the number of HyLIRG is maximum around z=2. We find that Normal galaxies, LIRG and ULIRG dominates the infrared output at z=0, z=1 and z=2, respectively. The HyLIRG accounts for a small fraction (<10%) at all redshifts.

We reproduce the CIB spectrum and predict contributions per redshift slice (see Fig. 2). We found that the mid- and far-infrared part of the CIB are mainly emitted by the normal galaxies and LIRG. The sub-mm part is mainly due to LIRG and ULIRG at high redshift in accordance with the sub-mm observations of deep fields. We estimate a CIB total value of 23.7$\pm$0.9 nW.m^{-2}.sr^{-1}.

We estimate the fraction of lensed sources in the sub-mm as a function of the flux and wavelength. This contribution is low (< 10%) below 500 μm, but high (up to 50%) around 100 mJy in the mm domain. We predict that the population of very bright dusty galaxies detected by SPT and without IRAS counterpart [16] is essentially composed of lensed sub-mm galaxies.

Our model also predicts the contribution of the lensed sources to the *Planck* number counts, the confusion limits for future missions like SPICA or CCAT and the opacity of the Universe to TeV photons (see details in [21]).

5. Conclusion

Our model reproduces the infrared observations with a rather simple evolution of the infrared galaxies as a function of redshift. This model do not need AGN and/or temperature scatter to reproduce the observations. Nevertheless, another very recent model [42] also reproduces the number counts with a different evolution of the galaxies. It shows that accurate measurements of the redshift distributions (Fig. 3) and of the fluctuations (e.g. with Planck and Herschel [43, 44]) will be helpful to discriminate this new generation of model in the future.

The material of the model (software, tables and predictions) is available at http://www.ias.u-psud.fr/irgalaxies/.

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