Measurements of the Spectral Energy Distribution of the Cosmic Infrared Background

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The extragalactic background light (EBL) is the relic emission of all processes of structure formation in the Universe. About half of this background, called the Cosmic Infrared Background (CIB) is emitted in the 8-1000 microns range, and peaks around 150 microns. It is due to the dust reemission from star formation processes and AGN emission. The CIB spectral energy distribution (SED) constraints the models of star formation in the Universe. It is also useful to compute the opacity of the Universe to the TeV photons. We present the different types of measurements of the CIB and discuss their strengths and weaknesses.

1. The absolute SED was measured by COBE, and by other experiments. These measurements are limited by the accuracy of the component separation, i.e. the foreground subtraction.

2. Robust lower limits are determined from the extragalactic number counts of infrared galaxies. These lower limits are very stringent up to 100 microns. At larger wavelengths, the rather low angular resolution of the instruments limits strongly the depth of the number counts. The "stacking" method determines the flux emitted at a given wavelength by a population detected at another wavelength, and provides stringent lower limits in the sub-mm range. It is complementary with other methods based on the statistical analysis of the map properties like the P(D) analysis.

3. Finally, upper limits can be derived from the high energy spectra of extragalactic sources. These upper limits give currently good constraints in the near- and mid-IR.

Progress have been amazing since the CIB discovery about 15 years ago: the SED is much better known, and most of it can be accounted for by galaxies (directly or indirectly). Prospects are also exciting, with fluctuation analysis with Planck & Herschel, and forthcoming missions.

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1. Introduction

The cosmic infrared background (CIB) was detected for the first time in the late nineties in the FIRAS and DIRBE data [1 – 3]. This background, lying in the mid- far-infrared and submillimeter range (usually defined between 8 and 1000 μm), represents about half [4] of the extragalactic background light (EBL), which is the relic of all the structure formation processes. The CIB emission is mainly due to the outputs of the infrared galaxies, and in a minor way to the obscured active galactic nuclei (AGN) [5, 6]. It peaks near 150 μm .

The output of the infrared galaxies is a good probe of the star formation [7]. During a starburst, the massive stars have short lives but strong UV emissions, which are absorbed and reprocessed by the dusty environment where they formed. Infrared outputs are thus a probe of the presence of massive young stars and thus of the recent star formation in a galaxy. Dust heated by AGN also contribute to the CIB, but almost an order of magnitude fainter than starbursts [8]. The spectral energy distribution (SED) of the CIB thus constrains the star formation history and the galaxy evolution models [9 – 13].

2. Direct measurements

Direct measurements of the CIB can be performed using absolute photometry, but these measurements are affected by the accuracy of the foreground modeling. These foregrounds are the zodiacal emission [14] and the galactic cirrus [15]. The zodiacal emission is the thermal radiation of the interplanetary dust. The galactic cirrus are diffuse clouds of dust in our galaxy heated by the UV emissions of the stars. At 20 μm, the zodiacal light is three order of magnitude brighter than the CIB. The accuracy of the zodiacal subtraction is thus the main limitation of the absolute measurements. The galactic cirrus output have the same order of magnitude than the CIB. They can be removed accurately using the current HI data [16]. At larger wavelength, the cosmic microwave background have to be subtracted. The spectrum of the CMB being well known, its subtraction can be done accurately [17].

First measurements of the CIB was performed with DIRBE [3] and FIRAS [2, 15] onboard COBE. The DIRBE measurements have been updated in [4] (see discussion about DIRBE/FIRAS cross-calibration and subtraction of the zodiacal light). More recent measurements have been performed with, ISO [18], Akari [19] and *Spitzer* [16]. These measurements are summarized in the Fig. 1 and Table 1. Notice the large scatter in the measurements. Notice also the IRAS measurements [20] based on a fluctuation analysis.

3. Lower limits from the number counts

In the mid-infrared, the depth and the angular resolution of the recent infrared surveys is sufficient to resolve the main part of the CIB into sources. Stringent lower limits can thus be derived from the integration of the source counts. These lower limits were derived at 8 μm using the *Spitzer*/IRAC data [21], at 15 μm using ISO [31], *Spitzer* [22] and Akari [32] data, and at 24 μm [23]. Estimations of the total contribution of the galaxies to the CIB was done by extrapolating the
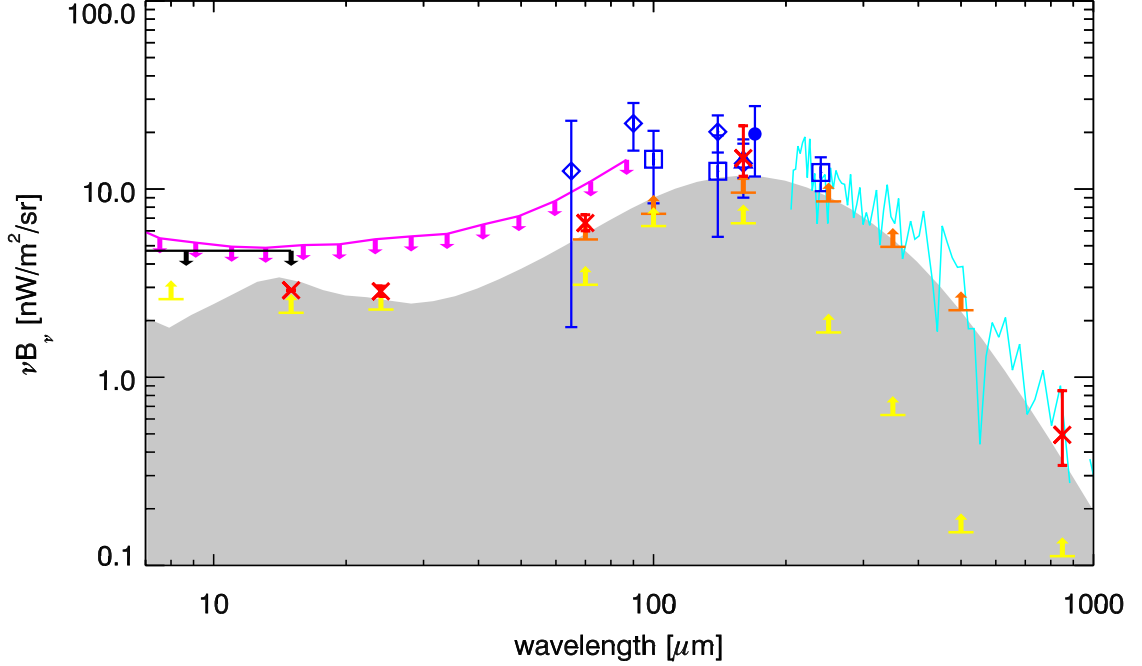
Figure 1: Spectral energy distribution of the cosmic infrared background. *Yellow arrows*: Lower limits from resolved source counts at 8 μm [21], 15 μm [22], 24 μm, 70 μm [23], 100 μm, 160 μm [24], 250 μm, 350 μm and 500 μm [25] and 850 μm [26]. *Orange arrows*: Lower limits from stacking analysis at 70 μm [23], 100 μm, 160 μm [24], 250 μm, 350 μm and 500 μm [27]. *Red crosses*: Extrapolated total contribution of the galaxies to the CIB at 15 μm [22], 24 μm, 70 μm, 160 μm [23] and 850 μm [28]. *Blue square*: DIRBE absolute measurements [3]. *Blue diamonds*: Akari absolute measurements [19]. *Blue triangle*: MIPS absolute measurement at 160 μm [16]. *Blue circle*: ISOPHOT absolute measurement at 170 μm [18]. *Cyan solid line*: FIRAS Spectrum [15]. *Black arrows*: Upper limits from TeV opacity of the Universe [29]. *Purple arrows*: Upper limits from TeV opacity of the Universe [30]. *Light grey area*: CIB predicted by the Bethermin et al. model [12].

faint-end slope of the counts. Assuming the CIB is only due to the galaxies, the fraction of the CIB resolved directly is then estimated to be $\sim$80% [23].

At larger wavelengths, the angular resolution of the instruments decreases compared to wavelength, and it is harder to resolve a significant part of the CIB due to the confusion [33, 34]. For example, we resolve only 40% and 15% of the CIB at 70 and 160 μm, respectively with *Spitzer* [23]. Thanks to its 3.5 m diameter mirror, *Herschel* resolves $\sim$45% and $\sim$52% at 100 and 160 μm, respectively [24]. Nevertheless, this fraction decreases to $\sim$15%, $\sim$10% and $\sim$6% at 250, 350 and 500 μm, respectively [25]. At 850 μm, the opacity of the atmosphere is sufficiently low to allow observations from the ground. The counts at this wavelength resolve only 20-30% of the CIB [26]. Deeper counts, resolving the bulk of the CIB, are derived in fields lensed by low-z galaxy clusters, where the error budget is dominated by the large scale structure (narrow field) [35, 28]. These measurements are summarized in the Fig. 1 and Table 1.

Wavelength μm	Reference	CIB level nW.m^{-2}.sr^{-1}	Instrument	Comments
		Absolute measurements		
65	Matsuura et al. (2009)	12.5±1.4±9.2	Akari	
90	Matsuura et al. (2009)	22.3±1.7±4.7	Akari	
100	Lagache et al. (2000)	14.4±6.0	DIRBE	Updated in Dole et al. (2006)
140	Lagache et al. (2000)	12.4±6.9	DIRBE	Updated in Dole et al. (2006)
140	Matsuura et al. (2009)	20.1±3.4±1.1	Akari	
160	Matsuura et al. (2009)	13.7±3.9±40.8	Akari	
160	Penin et al. (2011)	14.43±3	*Spitzer*/MIPS	
170	Juvela et al. (2009)	19.6±5.8±5.5	ISOPHOT	
240	Lagache et al. (2000)	12.3±2.5	DIRBE	Updated in Dole et al. (2006)
200-1000	Lagache et al. (2000)	see figure	FIRAS	
		Lower limit from resolved sources		
8	Fazio et al. (2004)	5.4	*Spitzer*/IRAC	QSO1700+EGS+Bootes
15	Teplitz et al. (2010)	2.2±0.2	*Spitzer*/IRS	GOODS-N and S
24	Béthermin et al. (2010)	2.29±0.09	*Spitzer*/MIPS	FIDEL+COSMOS+SWIRE
70	Béthermin et al. (2010)	3.1±0.2	*Spitzer*/MIPS	FIDEL+COSMOS+SWIRE
100	Berta et al. (2010)	6.33±1.67	*Herschel*/PACS	SDP data
160	Berta et al. (2010)	6.58±1.62	*Herschel*/PACS	SDP data
250	Oliver et al. (2010)	1.73±0.33	*Herschel*/SPIRE	SDP data
350	Oliver et al. (2010)	0.63±0.18	*Herschel*/SPIRE	SDP data
500	Oliver et al. (2010)	0.15±0.07	*Herschel*/SPIRE	SDP data
850	Coppin et al. (2008)	$0.11^{+0.05}_{-0.04}$	SCUBA	SHADES survey
		Lower limits from stacking analysis		
70	Béthermin et al. (2010)	5.4±0.4	*Spitzer*/MIPS	FIDEL+COSMOS+SWIRE
100	Berta et al. (2010)	7.4±0.5	*Herschel*/PACS	SDP data
160	Berta et al. (2010)	9.6±0.7	*Herschel*/PACS	SDP data
250	Marsden et al. (2009)	8.6±0.6	BLAST	biased by clustering (∼+9%)
350	Marsden et al. (2009)	4.9±0.3	BLAST	biased by clustering (∼+13%)
500	Marsden et al. (2009)	2.3±0.2	BLAST	biased by clustering (∼+24%)
		Extrapolated total contribution of the galaxies to the CIB		
24	Béthermin et al. (2010)	$2.86^{+0.19}_{-0.16}$	*Spitzer*/MIPS	direct extraction + stacking
70	Béthermin et al. (2010)	$6.6^{+0.7}_{-0.6}$	*Spitzer*/MIPS	direct extraction + stacking
160	Béthermin et al. (2010)	$14.6^{+7.1}_{-2.9}$	*Spitzer*/MIPS	direct extraction + stacking
850	Zemcov et al. (2010)	0.34-0.85	SCUBA	lensing survey
		Upper limits from γ-rays absorption		
5-15	Renault et al. (2001)	4.7	CAT & HEGRA	0.5-20 TeV
1-90	Mazin&Raue (2007)	5-40	TeV exp.	0.1-20 TeV

Table 1: Summary of the measurements of the cosmic infrared background.

4. More stringent lower limits from the statistical analysis of far-infrared maps

In the 200-800 μm range, the faint sources which contribute to the CIB cannot be resolved due to the limited angular resolution of current instruments. Nevertheless, most of these sources are detected in the deepest *Spitzer* 24 μm surveys. The collective signal of these sources, not detected individually in the FIR and sub-mm, can be detected collectively by stacking, providing very stringent lower limits on the CIB in *Spitzer*/MIPS [4, 23], BLAST [27], PACS [24] bands. It is also possible to compute deep number counts from stacking analysis and to derive an estimation of the total value of the CIB extrapolating the faint end-slope of the number counts [23].

Ultra-deep counts can also be derived from the analysis of the pixel histograms of the infrared maps – P(D) analysis [36, 37]. If the clustering of the galaxies is neglected and the sources are point-like, the pixel histogram depends only on the counts and instrumental properties (instrumental noise and PSF). A non-physical broken power-law description of the number counts can thus be fitted to this pixel histogram [38, 39]. This method provide deep counts which explains about 2/3 of the CIB at 250, 350 and 500 μm, and is complementary to the stacking analysis. These measurements are summarized in the Fig. 1 and Table 1.

5. Upper limits from the gamma-ray spectra

Two photons can interact if the energy in the barycentric frame is sufficient to produce a positron-electron pair. The high-energy γ photons can thus be absorbed by the photons of the EBL [40, 41]. This absorption can be detected as a break at high energy in the spectrum of high-redshift blazars. This phenomenon provides upper limits on the COB and the CIB [29]. Using the spectrum of several blazars, it is now possible to derive stringent upper limits to the CIB below 100 μm [30]. The method is somehow dependant on the assumed blazar spectra and on the evolution of the CIB with the redshift [42], but is extremely powerful in particular at near-infrared wavelengths (not covered here).

6. Conclusion

The direct measurements of the CIB are difficult because of the accuracy requirements on the foreground subtraction, despite a better knowledge and refined techniques. The lower limits coming from the deep surveys and the upper limits coming from the blazars spectra are more and more stringent, and the association of these two measurements challenges the absolute measurements, especially in the mid-IR, where the zodiacal emission is very strong. Other constraints, e.g. involving the build-up of the CIB with redshift [8] will allow even better observational constraints on the CIB SED and its history, not mentioning the detailed study of the CIB fluctuations (e.g. with Planck at large angular scales [43] and Herschel at small scales [44], following earlier works e.g. with IRAS, ISO, Spitzer, BLAST, Akari). The progress has been amazing since the CIB first detection 15 years ago, the SED being much better known (despite large uncertainties at some wavelengths, like between 30 and 120 microns), and most of the emission being explained

by directly or indirectly detected galaxy populations, mainly luminous and ultraluminous infrared galaxies.

In the future, these observational constraints will be significantly improved thanks to the next generation of telescopes. In the mid-IR and far-IR, JWST (6.5 m space telescope) will be able to resolve directly almost all the CIB at those wavelengths. These data will also be useful to perform deeper stacking analysis in the sub-mm. Finally, CCAT (25 m sub-mm ground-telescope) and ALMA (sub-mm interferometer) will be able to resolve directly the bulk of the CIB in the sub-mm domain [12], while awaiting possible future space missions dedicated to the study of CIB fluctuations and/or galaxies (e.g. space interferometers in the FIR).

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