The extragalactic background and its fluctuations in the far-infrared wavelengths

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Abstract. A Cosmic Far-InfraRed Background (CFIRB) has long been predicted that would traces the intial phases of galaxy formation. It has been first detected by [1] using COBE data and has been later confirmed by several recent studies ([2], [3], [4]). We will present a new determination of the CFIRB that uses for the first time, in addition to COBE data, two independent gas tracers: the HI survey of Leiden/Dwingeloo ([5]) and the WHAM H_α survey ([6]). We will see that the CFIRB above 100 μm is now very well constrained. The next step is to see if we can detect its fluctuations. To search for the CFIRB fluctuations, we have used the FIRBACK observations. FIRBACK is a deep cosmological survey conducted at 170μm with ISOPHOT ([7]). We show that the emission of unresolved extragalactic sources clearly dominates, at arcminute scales, the background fluctuations in the lowest galactic emission regions. This is the first detection of the CFIRB fluctuations.

1   Determination of the CFIRB above 100 μm: an other approach

In very diffuse parts of the sky (no molecular clouds and HII regions), the far-IR emission can be written as the sum of dust emission associated with

the neutral gas, dust associated with the ionised gas, interplanetary dust emission and the CFIRB (and eventually the cosmological dipole and CMB). In previous studies ([1], [2], [3]), dust emission associated with the ionised gas which was totally unknown has been either not subtracted properly or neglected.

We have detected for the first time dust emission in the ionised gas ([4]) and shown that the emissivity (which is the IR emission normalised to unit hydrogen column density) of dust in the ionised gas was nearly the same as that in the neutral gas. This has consequences on the determination of the CFIRB. Following this first detection, we have combined HI and WHAM H_α data ([6]) with far-IR COBE data in order to derive dust properties in the diffuse ionised gas as well as to make a proper determination of the CFIRB. Technically, after a careful pixel selection (see [8] for more details) we describe the far-infrared dust emission as a function of the HI and H^+ column density by:

$$IR = A \times N(HI)_{20cm^{-2}} + B \times N(H^+)_{20cm^{-2}} + C \tag{1}$$

where $N(HI)_{20cm^{-2}}$ and $N(H^+)_{20cm^{-2}}$ are the column densities normalised to 10^{20} H cm^{-2}. The coefficients A, B and the constant term C are determined simultaneously using regression fits. We show that about 25% of the IR emission comes from dust associated with the ionised gas which is in very good agreement with the first determination ([4]). The CFIRB spectrum obtained using this far-infrared emission decomposition is shown in Fig. 1 together with the CFIRB FIRAS determination of [4] in the Lockman Hole region. We see a very good agreement between the two spectra. These determinations are also in good agreement with [2].

At 140 and 240 μm, the values obtained for the CFIRB are 1.13±0.54 MJy/sr and 0.88±0.55 MJy/sr respectively For each selected pixel, we compute the residual emission, R = IR - A×N(HI) - B×N(H$^+$). Uncertainties of the CFIRB have been derived from the width of the histogram of R (statistical uncertainties derived from the regression analysis are negligible). The obtained CFIRB values, although much more noisy (due to the small fraction of the sky used), are in very good agreement with the determination of [3]. At 140 μm, the CFIRB value of [4] is smaller than that derived here since the assumed WIM (Warm Ionised gas) dust spectrum was overestimated (the WIM dust spectrum was very noisy below 200 μm and the estimated dust temperature was too high).

At 100 μm, assuming an accurate subtraction of the zodiacal emission, our decomposition gives: $I_{CFIRB}(100)$= 0.78±0.21 MJy/sr. This is the first time that two independent gas tracers for the HI and the H^+ have been used to determine the background at 100 μm. One has to note that methods based on the intercept of the far-IR/HI correlation for the determination of the CFIRB are dangerous. For example, for our selected parts of the sky, this intercept is about 0.91 MJy/sr, which is quite different from the value of the
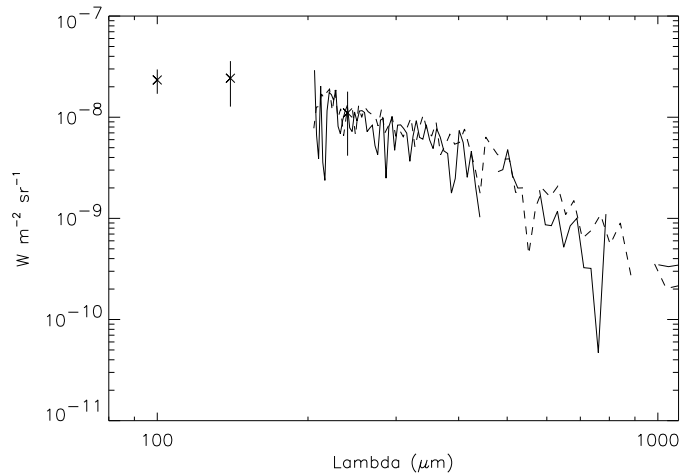
Fig. 1. CFIRB spectra obtained from the decomposition of the far-infrared sky (continuous line) and determined for the Lockman Hole region (dashed line) by [4]. Also reported are DIRBE values at 100, 140 and 240 μm.

CFIRB (0.78 MJy/sr). The CFIRB value of 0.78 MJy/sr can be compared to the non-isotropic residual emission found by [3]. The average over three regions of the residual emission, equal to 0.73±0.20 MJy/sr, is in very good agreement with our determination.

So we see, using different approaches, that we are now converging on the shape and level of the CFIRB above 100 μm. The next step is to see if we can detect its fluctuations and study them.

2   Why search for the CFIRB fluctuations?

The CFIRB is made of sources with number counts as a function of flux which can be represented, for the present discussion, by a simple power law:

$$N(> S) = N_0 \left(\frac{S}{S_0} \right)^{-\alpha}$$

Obviously, these number counts need to flatten at low fluxes to insure a finite value of the background. Thus, we assume that $\alpha=0$ for $S < S^*$.

For the simple Euclidian case ($\alpha=1.5$), the CFIRB integral is dominated by sources near S^* and its fluctuations are dominated by sources which are just below the detection limit S_0. It is well known that strong cosmological evolution, associated with a strong negative K-correction, could lead to a very

steep number count distribution (see for example [9] and [10]). In the far-IR present observations show a very steep slope of α=2.2 ([7]). In this case, the CFIRB integral is still dominated by sources near S* but its fluctuations are now also dominated by sources close to S*. Thus, it is essential to study the extra-galactic background fluctuations which are likely to be dominated by sources with a flux comparable to those dominating the CFIRB intensity.

To see if we can detect the CFIRB fluctuations, we need wide field far-IR observations with high angular resolution and very high signal to noise ratio. The FIRBACK project, which is a very deep cosmological survey with ISOPHOT at 170 μm ([7]), sustains all these conditions. To search for CFIRB fluctuations, we have first used the so-called "Marano 1" field for which we obtained 16 independent coadded maps which allow us to determine very properly the instrumental noise. In this field, we have a signal to noise ratio of about 300 and we detect 24 sources ([11]) that we remove from the original map. We then extend our first analysis to the other FIRBACK fields. Details on the data reduction and calibration can be found in [12].

Source subtracted maps show background fluctuations which are made of two components that we want to separate, galactic cirrus fluctuations and if present the extra-galactic ones.

3   Extra-galactic and galactic background fluctuation separation: detection of the CFIRB fluctuations

Our separation of the extra-galactic and galactic fluctuations is based on a power spectrum decomposition. This method allows us to discriminate the two components using the statistical properties of their spatial behaviour. Fig. 2 shows the power spectrum of the "Marano 1" field. In the plane of the detector, the power spectrum measured on the map can be expressed in the form:

$$P_{map} = P_{noise} + (P_{cirrus} + P_{sources}) \times W_k \qquad (2)$$

where P_{noise} is the instrumental noise power spectrum measured using the 16 independent maps of the Marano 1 field ([13]), P_{cirrus} and $P_{sources}$ are the cirrus and unresolved extra-galactic source power spectra respectively, and W_k is the footprint power spectrum. For our analysis, we remove P_{noise} from P_{map}.

We know from previous work that the cirrus far-infrared emission power spectrum, P_{cirrus}, has a steep slope in $\sim k^{-3}$ ([14], [15], [16], [17], [18]). These observations cover the relevant spatial frequency range and have been recently extended up to 1 arcmin using very diffuse HI data ([19]). The extra-galactic component is unknown but certainly much flatter (see the discussion in [13]). We thus conclude that the steep spectrum observed in our data at

k<0.15 arcmin^{-1} (Fig. 2) can only be due to cirrus emission. The break in the power spectrum at k$\sim$ 0.2 arcmin^{-1} is very unlikely to be due to the cirrus emission itself which is known not to exhibit any prefered scale ([20]). Thus, the normalisation of our cirrus power spectrum P$_{cirrus}$ is directly determined using the low frequency data points and assuming a k^{-3} dependence.
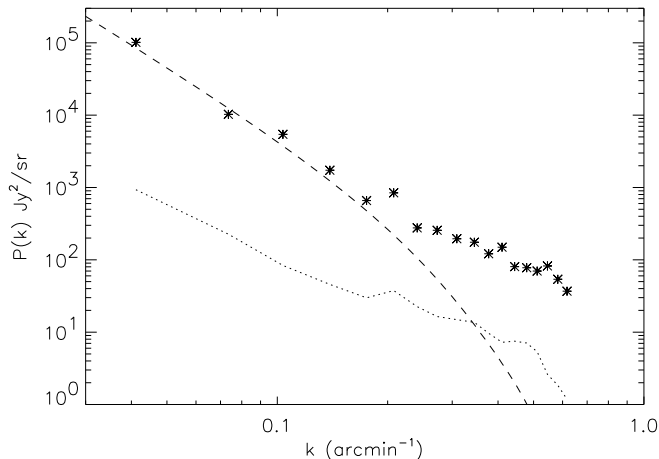
Fig. 2. Power spectrum of the source subtracted "Marano 1" field ($*$). The instrumental noise power spectrum (dotted line) has been subtracted. The dashed line represents the cirrus power spectrum, multiplied by the footprint.

We clearly see in Fig. 2 an excess over P$_{cirrus}$ between k=0.25 and 0.6 arcmin^{-1} which is more than a factor of 10 at k=0.4 arcmin^{-1}. Any reasonable power law spectrum for the cirrus component multiplied by the footprint leads, as can be easily seen in Fig. 2, to a very steep spectrum at spatial frequency k>0.2 arcmin^{-1} which is very different from the observed spectrum. Moreover, the excess is more than 10 times larger than the measured instrumental noise power spectrum. Therefore, as no other major source of fluctuations is expected at this wavelength, the large excess observed between k=0.25 and 0.6 arcmin^{-1} is interpreted as due to unresolved extra-galactic sources. This is the first detection of the CFIRB fluctuations.

The Marano 1 field cannot be used to constrain the clustering of galaxies due to it rather small size. However, the extra-galactic source power spectrum mean level can be determined. We obtain P$_{sources}$ = 7400 Jy^2/sr, which is in very good agreement with the one predicted by [21]. This gives CFIRB rms fluctuations around 0.07 MJy/sr (for a range of spatial frequencies up to 5

arcmin^{-1}). These fluctuations are at the $\sim$9 percent level, which is very close to the predictions of [22].

The same analysis can be done for the other and larger FIRBACK fields. From Eq. 2, we deduce:

$$P_{sources} = (P_{map} - P_{noise})/W_k - P_{cirrus}$$

Fig. 3 shows the extra-galactic fluctuation power spectrum ($P_{sources}$) obtained for the FIRBACK/ELAIS N2 field. It is very well fitted with a constant CFIRB fluctuation power spectrum of about 5000 Jy^2/sr, which is in good agreement with that obtained in the "Marano 1" field. We obtain also exactly the same extra-galactic fluctuation power spectrum in the FIRBACK N1 field with a value of about 5000 Jy^2/sr.
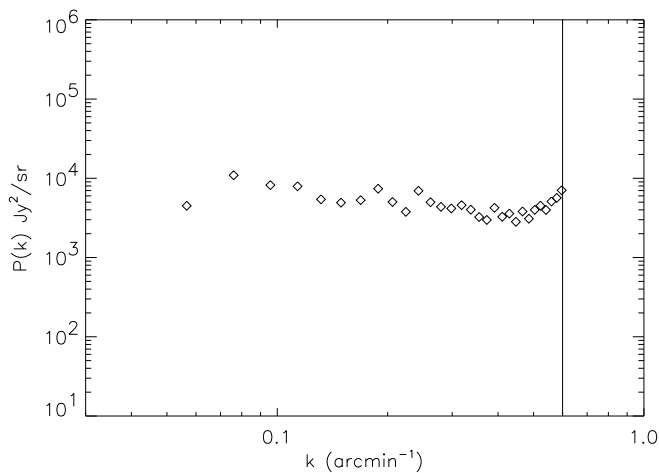
Fig. 3. Extra-galactic source power spectrum of the FIRBACK/ELAIS N2 field. The vertical line shows the cut-off in angular resolution.

4   Conclusions

We have shown in the FIRBACK fields that the extra-galactic background fluctuations lie well above the instrumental noise and the cirrus confusion noise. The observed power spectrum shows a flattening at high spatial frequencies which is due to unresolved extra-galactic sources. The level of the extra-galactic power spectrum fluctuations is nearly the same in all FIRBACK fields. The next step consists of removing the cirrus contribution using

independent gas tracers (the H$_\alpha$ and the 21cm emission lines) to isolate the extra-galactic fluctuation brightness and try to constrain the IR large scale structures.

References

1. Puget J.L., Abergel A., Bernard J.P., et al. 1996, A&A 308, L5
2. Fixsen D.J., Dwek E., Mather J.C., et al. 1998, ApJ 508, 123
3. Hauser M.G., Arendt R.G., Kelsall T., et al., 1998, ApJ 508, 25
4. Lagache G., Abergel A., Boulanger F., et al., 1999, A&A 344, 322
5. Hartmann D., Burton W.B., Atlas of Galactic neutral Hydrogen, Cambridge University Press, 1997
6. Reynolds R.J., Tufte S.L., Haffner L.M., et al., 1998, PASA 15, 14
7. Dole H., et al., this proceeding
8. Lagache G., Haffner L.M., Reynolds R.J., Tufte S.L., A&A, in press (Astroph/9911355)
9. Guiderdoni B., Hivon E., Bouchet F., Maffei B., 1998, MNRAS 295 , 877
10. Franceschini A., Andreani P., Danese L. 1998, MNRAS 296, 709
11. Puget J.L., Lagache G., Clements D.L. et al., 1999, A&A 354, 29
12. Lagache G., Dole H., to be submitted to A&A
13. Lagache G., J-L. Puget, A&A, in press (Astroph/9910255)
14. Gautier T.N.III, Boulanger F., Pérault M., Puget J.L., 1992, AJ 103, 1313
15. Kogut A., Banday A.J., Bennett C.L., et al., 1996, ApJ 460, 1
16. Herbstmeier U., Abraham P., Lemke D., et al., 1998, A&A 332, 739
17. Wright E.L., 1998, ApJ 496, 1
18. Schlegel D.J., Finkbeiner D.P., Davis M., 1998, ApJ 500, 525
19. Miville-Deschênes M.A., PhD thesis, Paris XI University
20. Falgarone, E. in "Starbursts: triggers, nature and evolution", Les Houches School, 1998, Ed. B. Guiderdoni & A. Kembhavi
21. Guiderdoni B., Bouchet B., Puget J.L., et al., 1997, Nature 390, 257
22. Haiman Z., Knox L., 1999, ApJ in press (Astroph/9906399)