Cosmic Microwave Background Polarisation: foreground contrast and component separation

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Abstract

We evaluate the expected level of foreground contamination to the cosmic microwave background (CMB) polarised radiation, focusing on the diffuse emission from our own Galaxy. In particular, we perform a first attempt to simulate an all sky template of polarised emission from thermal dust. This study indicates that the foreground contamination to CMB B modes is likely to be relevant on all frequencies, and even at high Galactic latitudes.

We review the recent developments in the design of data analysis techniques dedicated to the separation of CMB and foreground emissions in multi-frequency observations, exploiting their statistical independence. We argue that the high quality and detail of the present CMB observations represent an almost ideal statistical dataset where these algorithms can operate with excellent performance. We explicitly show that the recovery of CMB B modes is possible even if they are well below the foreground level, working at the arcmin. resolution at an almost null computational cost. This capability well represents the great potentiality of these new data analysis techniques, which should be seriously taken into account for implementation in present and future CMB observations.

1 Introduction

Among all cosmological observables, the Cosmic Microwave Background (CMB) polarisation stores cosmological perturbations in the smartest way. The Stokes parameters Q and U are non-locally combined to get the E and B modes, featuring opposite parity relations; as for total intensity (T), E modes are activated by all cosmological perturbations, and indeed the two are strongly correlated (TE); on the other hand, B modes are excited by vectors and tensors only; since no significant power is experted from vectors, a detection of B modes would be a strong indication of the presence of cosmological gravitational waves. For a comprehensive review of the CMB physics, see Hu et al. (1998) and references therein.

On the observation side, we are right now in the epoch in which the CMB is revealing its finest structure. The Wilkinson Microwave Anisotropy Probe

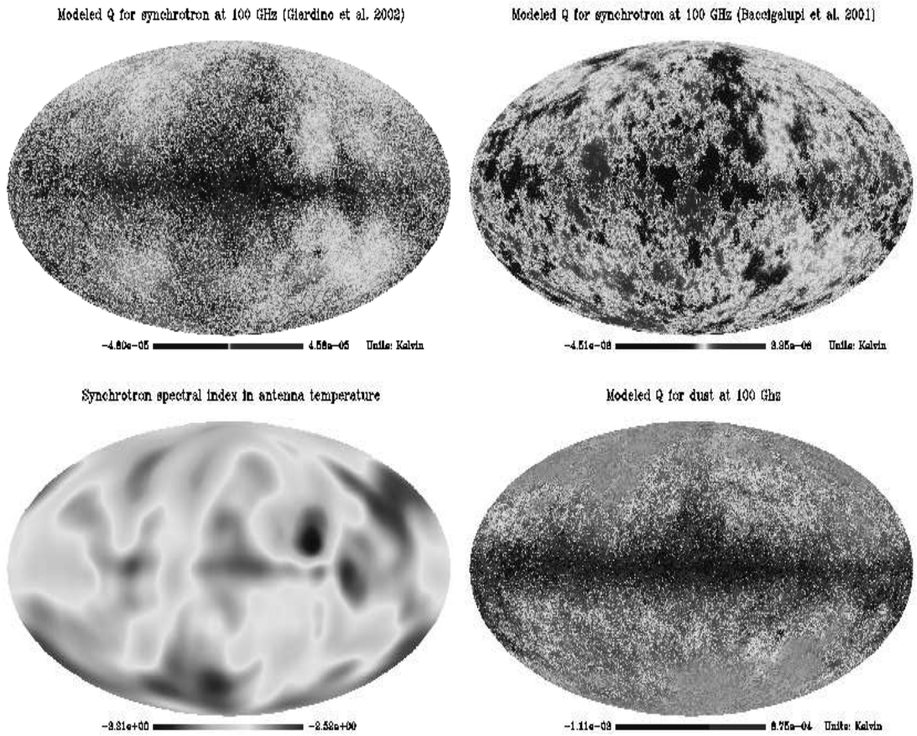

Figure 1: Upper panels: simulated templates for the synchrotron Q Stokes parameter. Lower left panel: synchrotron spectral index template. Lower right panel: Q simulated template for the dust.

(WMAP) satellite[1] released recently the first year CMB data, for T and TE, unveiling all sky anisotropies with about 20 arcmin. resolution on a frequency range between 22 and 90 GHz (see Bennett et al., 2003, and references therein); balloon-borne and ground-based T observations cover angular scales from a few arcminutes to tens of degrees, and also aim at measuring CMB E and B modes (see Kovac et al., 2002, for a first E mode detection). The PLANCK satellite[2] will provide total intensity and polarisation full sky maps with $5'$ resolution and a sensitivity of a few μK, on nine frequency channels between 30 and 857 GHz.

This work focuses on the foreground contamination to the CMB polarised emission. This issue is gathering greater and greater attention as the importance of the CMB polarisation measurements increases (see De Zotti, 2002, for reviews). In Section 2 we estimate the expected strength of foreground polarised emission with respect to the CMB; in Section 3 we describe the recent progresses in the design of data analysis tools designed to reduce such a contamination; in Section 4 we make some concluding remarks.

[1] map.gsfc.nasa.gov

[2] astro/estec.esa.nl/SA-general/Projects/Planck

2 Foreground contamination to the CMB

We focus on the diffuse emission from our own Galaxy. Indeed, at microwave frequencies, the contamination from Galactic, extra-Galactic radio and infrared sources (see De Zotti, 2002, and references therein), as well as the polarised Sunyaev-Zel Dovich emission (see White, 2003, proceedings of this conference), are likely to be relevant for the damping tail of the CMB power spectrum, i.e. at arcmin. angular scales, corresponding to multipoles ℓ of the order 1000, which sets the limit of validity for our analysis.

The main diffuse foreground at low microwave frequencies, say $\lesssim 100$ GHz is expected from Galactic synchrotron. The available high resolution data in the radio band, approximately 10 arcmin., are at low and medium Galactic latitudes, $|b| \lesssim 20°$ (Duncan et al., 1999; Uyaniker et al., 1999); degree resolution data (Brouw & Spoelstra, 1976) cover about half of the sky and reach high latitudes. These templates have been used to evaluate the angular power spectrum of synchrotron in the radio band, up to arcmin. scale (Tucci et al., 2000; Baccigalupi et al., 2001; Giardino et al., 2002; Tucci et al., 2002; de Oliveira-Costa et al., 2003, proceedings of this conference).
Tucci et al. (2000) estimated $C_\ell^{E,B} \propto \ell^{-1.5\div-2}$, regardless of the Galactic region considered; note that the same behavior was quoted for the first time by Tegmark et al. (2000). Baccigalupi et al. (2001) found the same result, regardless also of the Galactic latitude, up to the highest probed $|b| \simeq 20°$; they also estimated the level of Faraday depolarisation to be important, but not such to mask substantially the true synchrotron emission; moreover, they estimated the power on super-degree angular scales, corresponding to multipoles $\ell \leq 200$, using the Brouw & Spoelstra (1976) data, finding a steeper behavior, $C_\ell \propto \ell^{-3}$. Giardino et al. (2002) estimated the power spectrum of the cosine and sine of the polarisation angle up to the arcmin. scale, and out of that constructed a spatial template assuming Gaussian distribution; the resulting pattern was then used to simulate templates for Q and U out of the total intensity Haslam map at 408 MHz, assumed to be synchrotron dominated and theoretically polarised at 75%; they also estimated the synchrotron spectral index as inferred by multifrequency radio observations. Tucci et al. (2002) extended the power spectrum analysis up to a few thousand multipoles, and de Oliveira-Costa et al. (2003) performed a detailed study of the E and B modes in the large scale data.

The CMB contamination from diffuse Galactic dust is much more uncertain. The main emission mechanism arises from the thermal emission of magnetized dust grains, which get locally aligned by the Galactic magnetic field (Lazarian & Prunet, 2002). Moreover, indications of a non-thermal dust emission, possibly connected with rapid rotations of the grains and extending to much lower frequencies, has been conjectured in several works, although in the WMAP data there is no evidence of such component (see Bennett et al., 2003, and references therein). In total intensity, a $6'$ resolution all sky template of dust emission is available at 100 μm, and on the basis of a correct interpretation it can be scaled at microwave frequencies and compared with the CMB (see Finkbeiner et al., 1999, and references therein). In polarisation, a great achievement has been obtained by Archeops (see Ponthieu et al., 2003, proceedings of this conference), which measured a $3-5\%$ polarised dust signal on the Galactic plane. On the basis of these two ingredients, we propose here a naively simu-

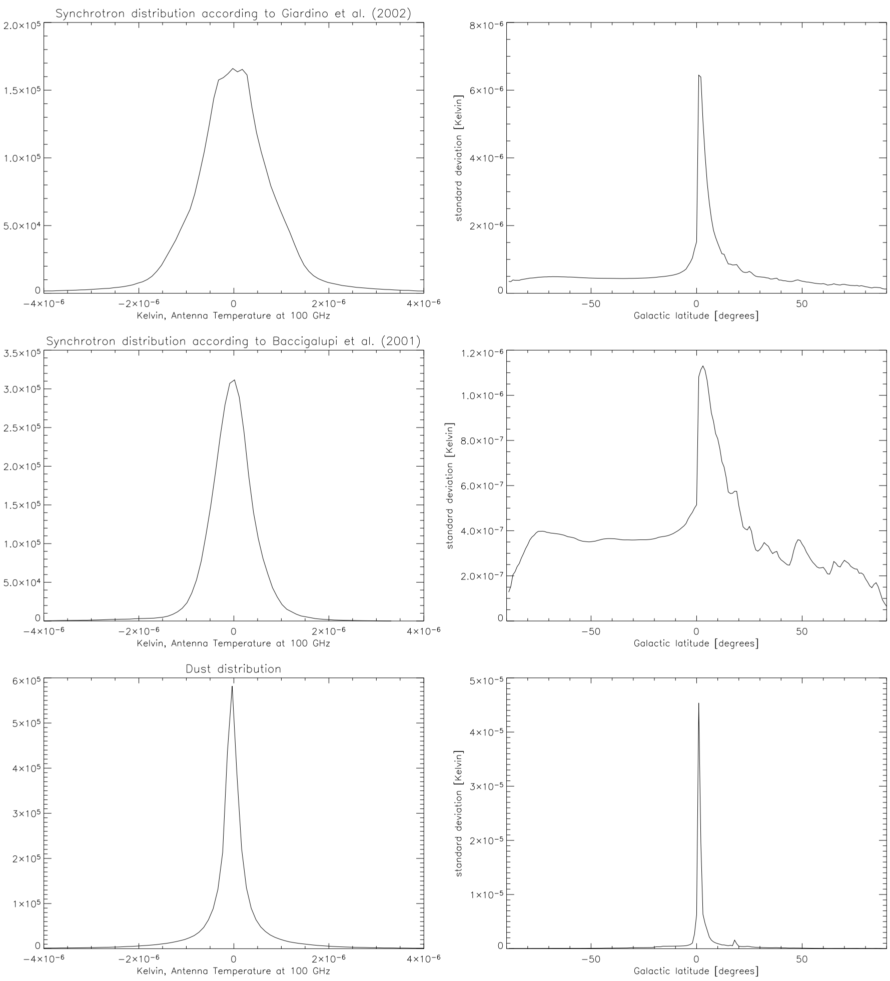

Figure 2: Signal distribution for the Stokes parameter Q (left) and Galactic latitude dependence (right) for S_G (top), S_B (middle) and dust (bottom), at 100 GHz.

lated template of the polarised dust emission, which agrees remarkably well with previous estimates (Lazarian & Prunet, 2002; Prunet et al., 2000). We assume perfect correlation between total and polarised intensity and a 5% polarisation degree. Then we assume the same polarisation angle pattern of the synchrotron emission (Giardino et al., 2002). That is certainly quite drastic, but it corresponds to the assumption that the Galactic magnetic field is 100% efficient imprinting the polarisation direction to the dust and synchrotron emission.

The Q Stokes parameter template[3] obtained by Giardino et al. (2002), hereafter S_G, is shown in figure 1, together with the spectral index template, upper and lower left panels, respectively; we also show the S_B template obtained rescaling S_G to match the power spectrum predicted by Baccigalupi et al. (2001),

[3]Unless otherwise specified, the maps and power spectra we show are in Kelvin, antenna temperature.

upper right panel; we also show the Q template for the polarised thermal dust emission as described above, in the right lower panel. S_G, S_B and dust are shown in a non-linear scale in order to highlight the behavior at high Galactic latitudes; the corresponding template for U is qualitatively equivalent; they have been extrapolated to 100 GHz, in antenna temperature, using the spectral index template for synchrotron and the latest recipe by Finkbeiner et al. (1999) for dust. By visual inspection, the S_B model appear to be less structured on small angular scales with respect to the S_G and the dust template; the latter has the sharpest decrease with Galactic latitude, as we discuss below.

Before quantifying the contamination to the CMB polarisation angular power spectrum, it is useful to give a look at the whole foreground statistics and sky distribution, plotted in figure 2; from top to bottom, the left and right panels represent signal distribution and root mean square as a function of b for S_G, S_B and dust. The signal distributions are far from Gaussianity, and exhibit a marked super-Gaussian behavior, as the total intensity maps from which all these templates were derived. Also, as we anticipated, the dust and S_B templates present the strongest and weakest dependence on the Galactic latitude, respectively. For the dust, the reason is the assumed perfect correlation between total and polarised intensity. For S_B, as we see now more in detail, most of the power lies on the small angular scales, which propagate well outside the Galactic plane.

In Fig. 3 we report the power spectra of the S_G, S_B and dust templates, compared to the CMB[4], on all sky and with a Galactic cut excluding the region with latitude $|b| \leq 20°$. The plots are at 100 GHz, in antenna temperature. The synchrotron frequency scaling according to the template in figure 1 is approximately $[100/\nu\ (\mathrm{GHz})]^{5.5}$, making the contamination rapidly worse at lower frequencies. For the dust, the scaling is given by Finkbeiner et al. (1999), which in the frequencies of interest here, say the interval covered by WMAP and Planck, is approximately $\propto \nu^{4.7}/[\exp{(h\nu/k_B T_D)} - 1]$, where h and k_B are the Planck and Boltzmann constant, and the thermodynamical dust temperature $T_D \simeq 18$ Kelvin; the departure from a pure black body behavior is due to the heating that the interstellar medium gets from stars (see Prunet et al., 2000, and references therein). The CMB fluctuations in antenna temperature scale as the derivative of the black body brightness $\propto \nu^2 \exp{(h\nu/k_B T_{CMB})}/[\exp{(h\nu/k_B T_{CMB})} - 1]^2$. As a general feature, it can be noted how the Galactic emission has almost equal power on E and B modes, according to the most natural expectation for a non-cosmological signal (Zaldarriaga 2001).
On a full sky analysis, the polarised dust dominates. This is likely to be the case if the observed $3-5\%$ polarisation degree really holds for all scales and the polarisation angle statistics is not too far from the synchrotron one. On the other hand, this signal does show the most abrupt drop when the Galaxy is cut out, which cleans almost completely the CMB E and TE modes, remaining however substantial for the B ones; note that this case agrees remarkably well with the level quoted by Prunet et al. (2000) at intermediate Galactic latitudes. On all sky, the synchrotron contamination is severe on large angular scales, almost covering the CMB reionization bump for E and B, being somewhat less important for TE. On E, the S_B signal drops rapidly below the CMB at a few

[4] We realize a CMB template according to the WMAP data: $h = 0.72$, $\Omega_\Lambda = 0.7$, $\Omega_b h^2 = 0.0228$, $\tau = 0.117$, $n_S = 0.96$, also assuming a tensor to scalar ratio $r = 30\%$, rather close to the current upper limit (see Bennett et al., 2003, and references therein).

tens in ℓ, while S_G affects the first CMB E acoustic oscillation. An important point is that the Galactic cut is not as effective as for the dust: the reason is the weaker Galactic latitude dependence for synchrotron, as it is evident in figure 2. As a result, the CMB B modes are likely to be severely contaminated even when the Galaxy is cut out.

We conclude that our present knowledge of the diffuse Galactic polarisation emission indicate that CMB TE and E modes are relatively clean, at least at medium and high Galactic latitudes and at frequencies around 100 GHz, while the B modes are likely to be severely contaminated, at all frequencies and Galactic latitudes.

3 Component Separation

Despite of the severe foreground contamination, the CMB B modes are expected to carry most important details on the nature of cosmological perturbations, as we stressed in the Introduction. For this reason it is worth to study data analysis techniques capable to clean the CMB from foreground contamination. This is feasible by exploiting the statistical differences of CMB and diffuse foregrounds, starting from a wide enough multi-frequency coverage of a given observation. The data can be sketched as

$$\mathbf{x}(n_f, n_p) = \mathbf{A}(n_f, n_c) \cdot \mathbf{s}(n_c, n_p) + \mathbf{n}(n_f, n_p) \ , \tag{1}$$

where $\mathbf{x}$ represents the data at the n_f frequencies, $\mathbf{s}$ the n_c components corresponding to each emission, and $\mathbf{n}$ the instrumental noise; $\mathbf{A}$ is the mixing matrix, scaling and mixing the emissions $\mathbf{s}$ at any observed frequency, while n_p is the number of pixels of the observation, or equivalently the number of harmonic coefficients if the analysis is performed in the spectral domain. Note that in general the angular resolution varies among the frequency channels. The target is to recover $\mathbf{s}$ from $\mathbf{x}$; as we saw in the previous Section, the problem is undetermined since we know $\mathbf{A}$ only partially, and the guesses on $\mathbf{s}$ are not reliable for stabilizing the inversion of the relation (1), either if the noise statistical properties are very well known, or even in a noiseless case. On the other hand, a well established expectation is that the CMB and foreground emission are statistically independent. It has been recently shown that this feature can be exploited to design "blind" component separation tools, i.e. able to recover $\mathbf{s}$ even without any prior on $\mathbf{s}$ or $\mathbf{A}$; a first algorithm of this class was proposed for use in astrophysical component separation by Baccigalupi et al. (2000) based on the novel concept in signal processing science, the Independent Component Analysis: that works by finding a $\mathbf{W}(n_c, n_f)$ matrix which applied to $\mathbf{x}(n_f, n_c)$ in (1) brings to $\mathbf{s} + \mathbf{W}\mathbf{n}$. The criterion to find $\mathbf{W}$ is to look for the statistically independent patterns in $\mathbf{x}$: that is clearly not unique and can be specialized for the problem at hand. A fast version (FastICA) adapted for satellite observations has been proposed by Maino et al. (2002); this technique has been further developed to account for any available and reliable prior, and successfully applied to the real COBE data by Maino et al. (2003). Recently, a different and promising blind technique based on a spectral matching of real and modeled data Delabrouille et al. (2003).

The first application of component separation to polarisation radiation has been performed by Baccigalupi et al. (2003), with a FastICA approach: sep-

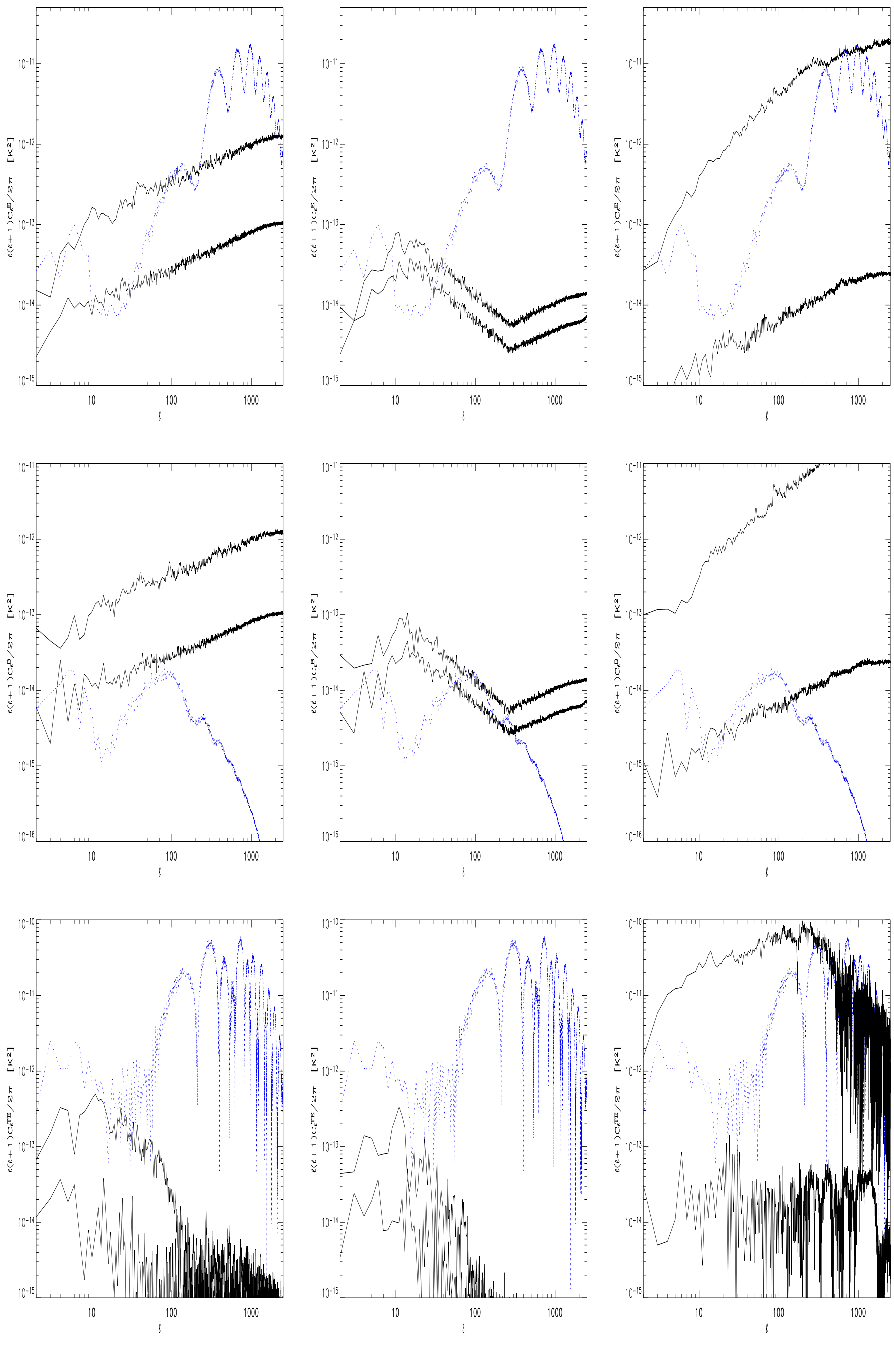

Figure 3: Expected angular power spectrum from S_G (left panels), S_B (middle panels) and dust (right panels) with respect to the CMB (dotted); in all panels, foreground contamination is calculated on all sky and with a Galactic cut for $|b| \leq 20°$.

aration is conducted on Q and U Stokes parameters separately or considered as a single signal provided that they obey the same statistics; we refer to that work for any detail on the algorithm procedure. Here we show a very simple application, with rather impressive results, to highlight the potentialities of this technique. We consider a noiseless mixture of polarised CMB and synchrotron S_G, scaling uniformly in frequency, at 50 and 80 GHz, on all sky and pixel size of about 3.5 arcmin.; note that we do not refer to any operating or planned experiment, and choose the frequencies among those in which CMB and synchrotron are roughly comparable. The two channels are input to the FastICA to recover synchrotron and CMB separately. Figure 4 show the input sky angular power spectra for E (left) and B (right) together with the spectra of the recovered CMB as output by FastICA. As it is evident, a CMB major cleaning was achieved: the dotted line is the input sky B power, while the recovered CMB (solid) line is actually almost indistinguishable from the input one (dashed). We stress that this is without the use of any prior, i.e. not knowing any piece of $\mathbf{A}$ or $\mathbf{s}$. The algorithm knows only the data at the two frequencies, and looks for the most statistically independent components in those data. In addition, applying this technique in particular is computationally free: the results in figure were obtained in about five minutes on an ordinary single processor personal computer.
In particular, the CMB B modes have been impressively cleaned: interpreting the foreground emission as noise, the signal to noise ratio is 0.1 or less, at all multipoles, as it can bee seen in the right panel of the figure. CMB E modes have also been cleaned wherever the foreground contamination was relevant. The algorithm outputs also $\mathbf{A}$, which differs from the real one by percent or less.

The reason of such an excellent performance is just the high level of detail of the underlying data. At arcmin. resolution, the maps are almost ideal datasets where the algorithm can look for the least statistically linked templates present into the maps themselves. Even if all the instrumental details were neglected, what we show here should be enough to gather attention on these new data analysis techniques, as we further stress in the next Section.

4 Concluding remarks

In this work we show that at frequencies around 100 GHz the diffuse Galactic polarisation emission is likely to be rather weak in comparison to the CMB TE and E modes, at least at medium and high Galactic latitudes, while the B ones are seriously contaminated on all sky. At lower and higher frequencies, the contamination gets rapidly worse because of the steep frequency behavior of synchrotron and dust, respectively.

We stress that the new concepts in signal processing science can be exploited in this context, to cancel or greatly reduce such a contamination. In particular, the statistical independence of CMB and foreground emission is suitable to achieve this goal: we give an impressive example based on the FastICA technique in polarisation (Baccigalupi et al., 2003), where CMB B modes are recovered out of a foreground emission about ten times stronger, without any prior information but their statistical independence, and at an almost null computational cost.

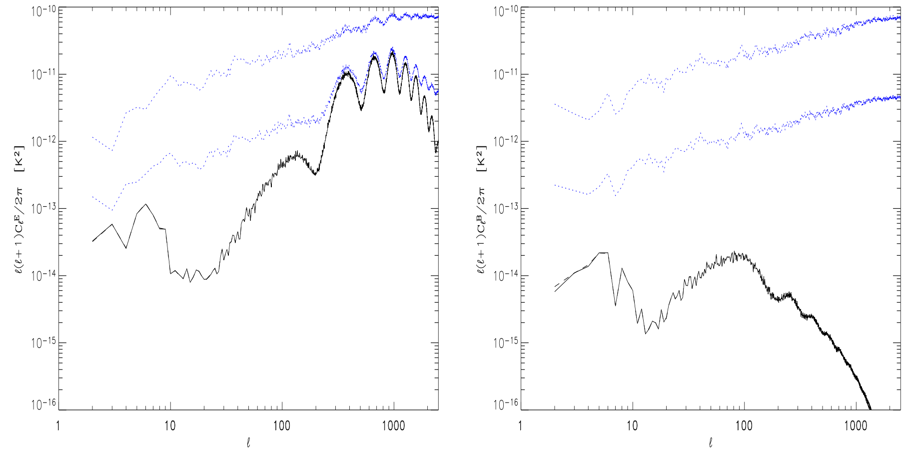

Figure 4: E and B modes of the original sky at 50 and 80 GHz (respectively high and low dotted curves) and recovered CMB E and B modes after component separation (solid), at 80 GHz; the true CMB (dashed), almost indistinguishable from the recovered one, is also plotted.

These features represent the "nominal" capabilities of these algorithms, i.e. their performance on ideal datasets: cleaning the cosmological signal from substantial foreground contamination, exploiting only their natural diversity. This is in our opinion a great achievement, providing the basis on which the implementation to any particular observation can be built. The latter step, of course, presents challenging issues: the noise level, sky distribution and non-stationarity, as well as the non-uniform spectral index of the components to recover, are good examples. However, we have already the indications of a substantial stability of the nominal performance against instrumental features and systematics: Maino et al. (2002) and Baccigalupi et al. (2003), respectively for total intensity and polarisation, perform a whitening of simulated Planck data in order to get rid of the noise bulk in the FastICA separation process. Most importantly, the results of Maino et al. (2003) show that these techniques are flexible enough to be applied to real data, the COBE ones, getting outstanding results, namely the correct large scale CMB power spectrum amplitude and shape.

While waiting for the era of large scale CMB polarisation measurements, the next obvious target is a successful application to the WMAP data, meaning the recovery of CMB data on sky regions affected by Galactic contamination which are normally cut out.

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