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The Planck mission after WMAP:

methodological aspects and cosmological implications

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Abstract. After a description of the Planck sensitivity in terms of angular power spectrum recovery in temperature and polarization, we discuss the main aspects of the removal of the systematic effects and foregrounds and some of the Planck cosmological implications.

Key words. Cosmology: cosmic microwave background – space missions

1. Introduction

Planck [1] will measure the temperature and polarization anisotropies of the cosmic microwave background (CMB) on the whole sky with high sensitivity and resolution on a wide frequency range. The performance of a given experiment can be described by its "nominal" relative uncertainty in the recovery of the unconvolved CMB anisotropy angular power spectrum, C_ℓ, due to the cosmic and sampling variance and instrumental white noise: $(\delta C_\ell/C_\ell)_{\rm cv,sv,wn} = \sqrt{2/[f_{\rm sky}(2\ell+1)]}[1+A\sigma^2/(NC_\ell W_\ell)]$. Here A is the size of the surveyed area, $f_{\rm sky} = A/4\pi$, N is the total number of pixel observed with a rms noise σ, and $W_\ell \simeq \exp(-\ell(\ell+1)\sigma_{\rm B}^2)$ is the beam window function ($\sigma_{\rm B} = {\rm FWHM}/\sqrt{8\ln 2}$). If $\sigma = 0$, the cosmic and sampling variance completely determines $\delta C_\ell/C_\ell$ (for WMAP and Planck it occurs in practice at $\ell \lesssim 100$). Fig. 1 compares the Planck and WMAP [2] absolute accuracy (neglecting cosmic and sampling variance) in the recovery (ℓ by ℓ) of the CMB C_ℓ at some representative frequencies.

2. Systematics and foregrounds

The extremely accurate control of all instrumental systematic effects is crucial at Planck sensitivity levels. On the other hand, thanks to the high Planck sensitivity it is possible to apply several kinds of algorithms to remove sys-

[1] http://astro.estec.esa.nl/

[2] http://lambda/gsfc.nasa.gov

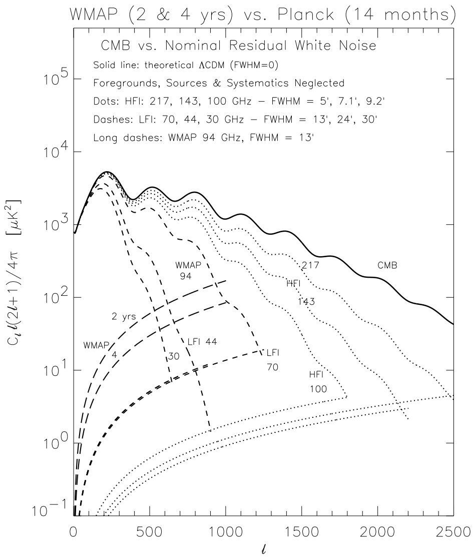

Fig. 1. Comparison between Planck and WMAP performances. The crossing between the CMB angular power spectrum convolved with the appropriate beam ($C_\ell W_\ell$) and the residual (i.e. the rms of the) instrumental white noise angular power spectrum ($\delta C_\ell = 4\pi\sigma^2 \sqrt{2/(2l+1)}/N$) defines the multipole where the S/N ratio in the C_ℓ recovery becomes $\lesssim 1$. Binning C_ℓ over a suitable range of ℓ, as possible because of the smooth variation of C_ℓ with ℓ, will improve the accuracy, particularly at high ℓ (for example at 70–100 GHz a $\sim 3\%$ binning over ℓ reduces the Planck uncertainty to $\sim 15\%$ at $\ell \sim 1500$). See also the text.

tematic effects. 1/f noise and thermal drifts, preliminarly reduced through an accurate design and realization of 4K reference loads and sorption coolers, will be further subtracted during the data analysis through dedicated destriping methods (see, e.g. Keihanen et al. 2003,and references therein), instrument monitoring (see, e.g., Maris et al. *this issue*) and map making codes (Natoli et al. 2001). Destriping methods are blind by construction while map making requires an accurate noise parametrization available from instrument ground testing and in-flight analysis. The correction of the effect on the data from optical distortions (Burigana et al. 1998), preliminarly reduced through an appropriate optical design study (see Sandri et al. *this issue*), requires to accurately reconstruct the main beam (Burigana et al. 2002) and to use specific algorithms, such as dedicated blind deconvolution algorithms jointed to Monte Carlo simulations for the subtraction of the deconvolved noise (Burigana & Sáez 2003). The straylight effect due to the beam far sidelobes, although kept at low levels, will be non negligible for Planck (Burigana et al. 2003). Dedicated simulations and ground measures of the far beam necessary for the straylight reduction during the data analysis are on-going.

The Planck central frequencies are the most favorable for CMB measures, being close to the minimum of the foreground fluctuations occurring at $\sim$ 60 GHz at scales $\gtrsim 0.5°$ (because of the large scale Galactic emission; Bennett et al. 2003) and at $\sim 100-150$ GHz at scales $\lesssim 0.5°$ (because of the confusion noise of extragalactic sources; Toffolatti et al. 1998). The overall foreground angular power spectrum shows a broad minimum at $\ell \sim$ few $\times$ $10 - 10^3$, just in the region of CMB acoustic peaks. In spite of these lucky circumstances, the accurate cosmological exploitation of the Planck data needs a very careful foreground removal. Dedicated accurate blind and non blind (such as FastICA, MEM, ...) methods of component separation have been recently developed and successfully applied to real and simulated data, in temperature and polarization (see, e.g., Baccigalupi et al. 2002, and references therein). They can work on multifrequency maps (both in real and harmonic space) or on time ordered data, the latter choice being necessary for the separation of the Solar System components or in presence of significant source variability (see Terenzi et al. *this issue*). Component separation methods have been designed to include or not auxiliary informations from surveys at different frequencies. The spatial correlation properties and/or the phase correlations of the map spherical harmonic expansion (Naselsky et al. 2003). have been also exploited to separate CMB from foregrounds. The removal of the extragalactic sources can be obtained by exploiting radio and far IR catalogs and by using dedicated filters (e.g. wavelets). All these methods applied

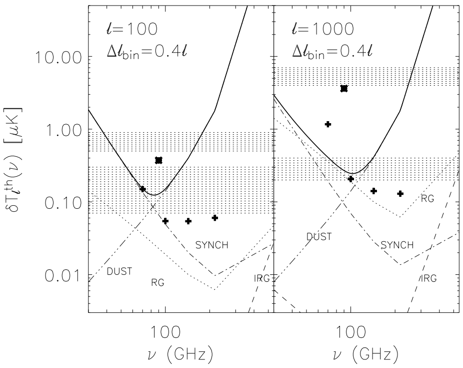

Fig. 2. Comparison between Planck and WMAP polarization performances at $\ell \sim 10^2$ and 10^3 as function of the frequency. The Planck HFI 100 GHz polarization channel, currently under implementation, is assumed here to have a sensitivity close to that at 143 GHz. See also the text.

to the Planck data will allow to accurately image the most significant components of the microwave sky.

3. Polarization

The ET-mode angular power spectrum has been recently measured by WMAP (Kogut et al. 2003) while a first measure of the E-mode angular power spectrum has been obtained by DASI (Kovac et al. 2002). Interesting upper limits have been also obtained by the POLAR, PIQUE, and COMPASS experiments. Fig. 2 compares the final sensitivity of WMAP at 94 GHz (asterisk) and of some Planck frequency channels (crosses) binned over a suitable range of multipoles with the foreground contamination (thick solid line) and the typical ranges of the CMB polarization C_ℓ including the lensing (E-mode, upper dotted regions; B-mode, lower dotted regions) predicted on the basis of WMAP and DASI results. In the estimate of the contribution from radiogalaxies (dots Tucci et al. 2004) we assume here a source detection threshold of $\sim$ 0.2 Jy. We report also the small contribution expected from IR galaxies (dashes) computed according to De Zotti et al. (1999) but by assuming a polarization degree of $\sim$ 0.4%. The Galactic synchrotron emission (dot-dashes) is here modelled according to Baccigalupi et al. (2001) and Burigana & La Porta (2002) and by taking also into account the POLAR upper limit (O'Dell et al. 2002) and the synchrotron slope found by WMAP (Bennett et al. 2003) for the extrapolation from radio to Planck frequencies. The dust contribution (three dots-dashes), dominant at $\nu \gtrsim 217$ GHz, is estimated from the WMAP 94 GHz dust template (at $|b| \geq 30°$) scaled according to the dust frequency slope (Bennett et al. 2003) and the typical polarization degree ($\sim$ 5%) found by ARCHEOPS (Benoit et al. 2003). At $\sim$ 100 GHz Planck will allow an accurate measure of the E-mode (see Fig. 2). Given an accurate foreground subtraction, the B-mode could be also detected by Planck at least at the CMB C_ℓ peaks expected at $\ell \sim 10^2$ and 10^3. At low ℓ, the sensitivity is not the major limitation, but the Galactic contamination may be a serious problem.

4. Some cosmological implications

Thanks to the Planck high accuracy in the determination of the CMB C_ℓ, a wide set of cosmological parameter will be measured with unprecedented accuracy almost independently of auxiliary astronomical and cosmological data, such as galaxy surveys and Ly-α systems (Popa et al. 2001, 2004), that will be then necessary only to break the intrinsic degeneracies in the CMB anisotropy information between some cosmological parameters (Bond et al. 1994). It will be also possible to firmly constrain the nature of the dark energy (see, e.g., Finelli et al. *this issue*). The accurate determination of CMB secondary acoustic peaks will allow to detect also the imprints from the non-linear gravitational clustering process, $\sim$ few $\times 10^{-6}$ in terms of $\Delta T/T$, depending on the main cluster properties as the mass and richness (Popa et al. 2002).

One of the most intriguing WMAP discovery is the high redshift reionization inferred by the Thomson scattering optical depth $\tau \sim 0.15$. The ionization history is determined by the balance between recombination and ionization. We consider here the parametrization of the efficiency of the ionizing photon production as modelled by Naselsky &

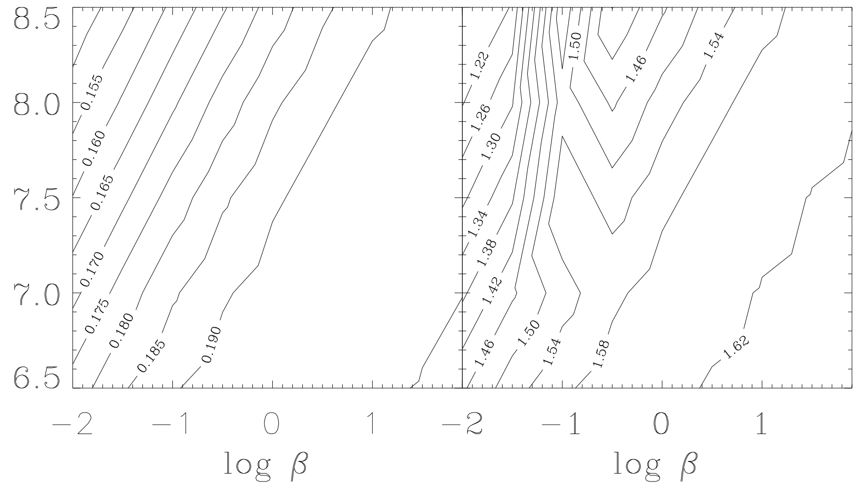

Fig. 3. Contour plots of τ (left panel) and $\Delta\epsilon/\epsilon_i \simeq 4u$ (in units of 10^{-6}, right panel) as functions of $\beta = \varepsilon_1/10^9$ and m (here $\varepsilon_0 = 1.3 \times 10^3$, $z_{reio} = 15$, and $\Delta z = 1.5$).

Chiang (2004): $\varepsilon_i(z) = \varepsilon_{i,G}(z)$ for early ($z \gtrsim 50$), possibly peak-like, reionization processes and $\varepsilon_i(z) = \varepsilon_{i,G}(z)+\varepsilon_1(1+z)^{-m}\Theta(z_{reio}-z)$ for late ($z \lesssim 20$) reionization processes, where $\varepsilon_{i,G}(z) = \varepsilon_0 \exp[-(z-z_{reio})^2/(\Delta z)^2]$. By considering a matter thermal history having a Gaussian parametric form similar to that considered for $\varepsilon_i(z)$ or mimicking the Cen (2003) model, respectively for early and late processes, Burigana et al. (2004) computed τ and the CMB Comptonization spectral distortion $u \simeq (1/4)\Delta\epsilon/\epsilon_i$ associated to the fractional energy injected in the plasma. Fig. 3 reports the results found for late processes. Planck will measure τ and the features left on the E-mode at various ℓ with the great sensitivity necessary to accurately probe different reionization scenarios, while future CMB spectrum space experiments with sensitivities similar to those proposed for DIMES and FIRAS II could observe the corresponding (Burigana et al. 2004) Comptonization and, possibly, free-free distortions.

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