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The Cosmic Microwave Background/Le rayonnement fossile à 3K

The Planck milestone

François R. Bouchet [a], Michel Piat [b,1], Jean-Michel Lamarre [c]

[a] Institut d'astrophysique de Paris, CNRS, 98 bis, bd Arago, 75014 Paris, France
[b] Institut d'astrophysique spatiale, Université Paris XI, 91405 Orsay, France
[c] LERMA, observatoire de Paris, 61, av de l'observatoire, 75014 Paris, France

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Abstract

Planck, a European Space Agency satellite to be launched in 2007, is dedicated to surveying the full sky at sub-millimetre and millimetre wavelength. The primary goal of the mission is the final mapping of the Cosmic Microwave Background Anisotropies (CMBA). With an angular resolution of 5 arcmin and a sensitivity of $\Delta T_{CMB}/T_{CMB} = 2 \times 10^{-6}$, the Planck mission will be about 1000 times more sensitive than COBE-DMR and at least 20 times more than WMAP. Planck has also very good capabilites for measurements of polarization, although it will not exhaust the information contained in the CMBA polarization pattern. Two instruments share the Planck focal plane; the High Frequency Instrument (HFI) covers the wavelength ranging from 300 μm to 3 mm by using 48 bolometers cooled to 100 mK. This instrument is realized by an international collaboration, led by the IAS at Orsay. The other part of the relevant electromagnetic spectrum is covered by the Low Frequency Instrument (LFI) using HEMT radiometers cooled at 18 K and realized by a consortium led by the CNR in Milano. The first part of this article presents expected results of Planck on CMBA, both in intensity and polarization. In a second part, the global design of the Planck mission will be presented. We describe in particular the implications of Planck scientific goals on the instruments design, and especially on HFI that is the most sensitive Planck instrument. ***To cite this article: F.R. Bouchet et al., C. R. Physique 4 (2003).***

Résumé

La mission Planck. Planck, un satellite de l'Agence Spatiale Européenne qui sera lancé en 2007, doit observer tout le ciel à des longueurs d'onde sub-millimétriques et millimétriques. Le premier objectif de la mission est la cartographie définitive des anisotropies du fond de rayonnement cosmique à 3K (CMBA). Avec une résolution angulaire de 5 arcmin et une sensibilité de $\Delta T_{CMB}/T_{CMB} = 2 \times 10^{-6}$, la mission Planck sera environ 1000 fois plus sensible que COBE-DMR et au moins 20 fois plus que WMAP. Planck dispose également de très bonnes capacités de mesures de la polarisation, bien qu'il n'épuisera pas l'information contenue dans la polarisation des CMBA. Deux instruments se partagent le plan focal de Planck ; l'instrument haute fréquence (HFI) couvrent des longueurs d'onde s'étalant de 300 μm à 3 mm grâce à l'utilisation de 48 bolomètres refroidis à 100 mK. Cet instrument est réalisé par une collaboration internationale dirigée par l'IAS à Orsay. L'autre partie pertinente du spectre électro-magnétique est couverte par l'instrument basse fréquence (LFI) qui utilise des radiomètres à base de HEMT refroidis à 18 K et qui est réalisé par un consortium dirigé par le CNR de Milan. La première partie de cet article présente les résultats attendus de Planck sur les CMBA, à la fois pour l'intensité et la polarisation. Dans une seconde partie, la conception générale de la mission Planck sera présenté. Nous décrivons en particulier les implications des objectifs de Planck sur le concept instrumental de HFI qui est l'instrument de Planck le plus sensible. ***Pour citer cet article : F.R. Bouchet et al., C. R. Physique 4 (2003).***

E-mail addresses: bouchet@iap.fr (F.R. Bouchet), piat@cdf.in2p3.fr (M. Piat), jean-michel.lamarre@obspm.fr (J.-M. Lamarre).
[1] Present address: Collège de France, laboratoire de physique corpusculaire et cosmologie, 11, place Marcelin Berthelot, 75231 Paris cedex 05.

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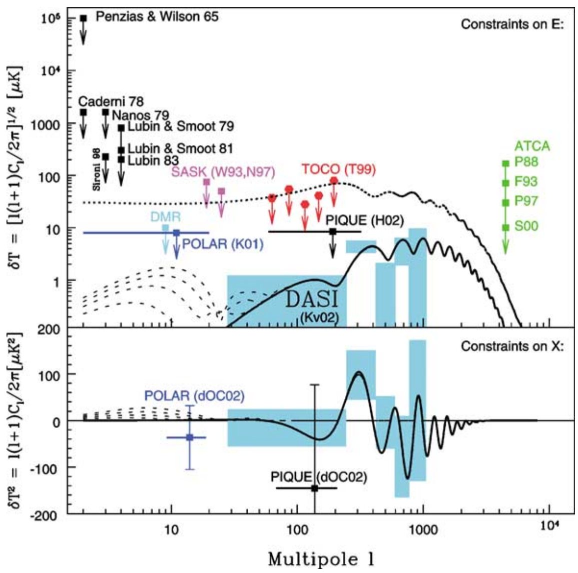
Mots-clés : Planck ; ESA ; Instrument haute fréquence ; Instrument basse fréquence ; Anisotropies du fond de rayonnement cosmique ; Cosmologie ; Univers primordial

1. Introduction

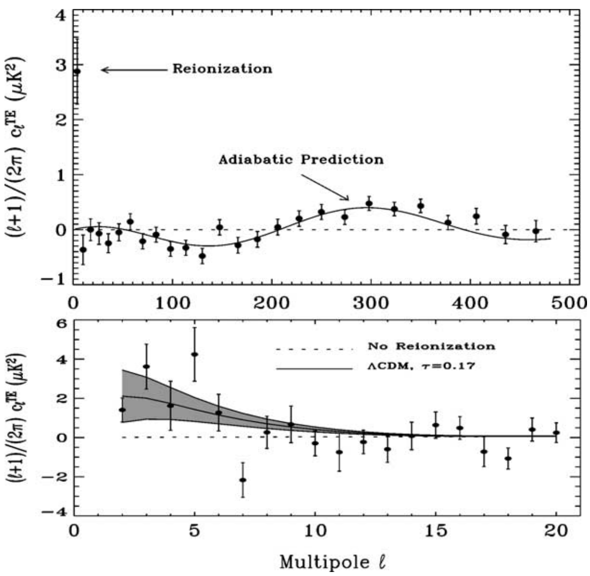
The DMR experiment on the COBE satellite obtained the first detection of the CMB anisotropies with a 7 deg beam and a signal to noise per pixel around 1. Many experiments followed and progressively unveiled the main features of the temperature anisotropies power spectrum by mapping small fractions of the sky, apart from the Archeops balloon experiment, a precursor of Planck-HFI, which covered 30% of the sky. The WMAP satellite recently confirmed earlier results, set new standards of accuracy, and dramatically increased our knowledge of the polarised part of the emission of the CMBA, as can be seen from Fig. 1. This second generation of experiments have an angular resolution usually approaching 10 arc minutes. The sensitivity is limited by uncooled detectors and/or by ambient temperature telescopes The third generation will be the Planck mission which will have a low background provided by its 40 K passively cooled telescope, which is large enough to provide 5 arc minute resolution, and bolometers cooled to 0.1 K, which will be photon noise limited.

The global similarities and differences of WMAP and Planck are the following:

- Both map the full sky, from an orbit around the Lagrangian point L2 of the Sun–Earth system, to minimise parasitic radiation from Earth. Both are based on the use of off-axis Gregorian telescopes in the 1.5 m class. Moreover, very importantly for CMB experiments, both do highly redundant measurements to better detect and remove (or constrain residuals of) possible systematics effect, thanks to the long duration of the data taking (at least a year, to be compared with, at most, about 10 days for ground experiments which have to cope, in addition, with the effect of a changing atmosphere – like ozone clouds, the closeness to earth, etc.). Both aim at making polarization measurements.
- The American WMAP has been designed for rapid implementation, and is based on fully demonstrated solutions. It's observational strategy uses a differential scheme. Two telescopes are put back to back and feed differential radiometers. These radiometers use High Electronic Mobility Transistors (HEMTs) for direct amplification of the radio-frequency (RF) signal. Angular resolutions are not better than 10 minutes of arc.



(a)



(b)

Fig. 1. Polarization measurements status: (a) pre-WMAP, with in the top panel a detection of the EE part in 2 bins (blue DASI boxes at $\ell \sim 300$ and 700). The lower panel shows the detection, in one ℓ-bin, of the cross-correlation TE [14,15]; (b) the WMAP determination of the TE spectrum, the bottom panel focusing on the low-ℓ part of the spectrum [13].

Table 1
Planck instrument characteristics. The sensitivities (1σ) are goal values for 12 months of integration and for square pixels whose sides are given in the row 'Angular Resolution'. Polarization measurement at 100 GHz on HFI is waiting for approval (the sensitivity level without polarization measurement at 100 GHz is given in parenthesis)

Detector technology	LFI			HFI					
	HEMT arrays			Bolometer arrays					
Center frequency [GHz]	30	44	70	100	143	217	353	545	857
Number od detectors	4	6	12	8 (4)	12	12	6	8	6
Bandwidth ($\Delta\nu/\nu$)	0.2	0.2	0.2	0.33	0.33	0.33	0.33	0.33	0.33
Angular resolution (arcmin)	33	241	14	9.2	7.1	5.0	5.0	5.0	5.0
$\Delta T/T$ per pixel (Stokes I) [$\mu K/K$]	2.0	2.7	4.7	2.5 (2.2)	2.4	3.8	15	17	8000
$\Delta T/T$ per pixel (Stokes Q and U) [$\mu K/K$]	2.8	3.9	6.7	4.1 (NA)	4.8	7.6	30	…	…

- The European Planck is a more ambitious and complex project, which is to be launched in 2007. It is designed to be the ultimate experiment in several respects. In particular, several channels of the High Frequency Instrument (HFI) will reach the ultimate possible sensitivity per detector, limited by the photon noise of the CMB itself. Bolometers cooled at 0.1 K will allow reaching this sensitivity while simultaneously, improving the angular resolution to 5 minutes of arc. The Low Frequency Instrument (LFI) limited at frequencies less than 100 GHz, will use HEMT amplifiers cooled at 20 K to increase their sensitivity. The Planck measurement strategy is of the total power type. The LFI uses 4 K radiative loads for internal references to obtain this total power measurement. The HFI readout scheme is based on an electric modulation of the detector allowing total power measurement. The combination of these two instruments on Planck is motivated by the necessity (see Section 2) to map the foregrounds in a very broad frequency range: 30 to 850 GHz.

More quantitative aspects are detailed in Table 1, although these are only indicative since the design evolves and in-flight performance may differ from the requirements (for better or worse, either way is possible).

2. The temperature power spectrum and foregrounds

Detector sensitivities can be very misleading since many other factors dictate the final accuracy that will actually be achieved on the CMBA measurements, and in particular on the power spectra. The ability to detect and remove the foreground contribution to the CMBA is a factor of increasing importance when the sensitivity improves. Given the sensitivity of the Planck detectors, great care in the design was taken to optimise the trade-off between good foreground control (many channels) and raw sensitivity (more detectors in a smaller number of channels).

To that effect, we developed a model of the statistical characteristics of the various microwave emissions in the context of the preparation for Planck [1,2]. One result of this modeling was estimates of the angular power spectra, $C(\ell)$, of the fluctuations of all the relevant components, as functions of the frequency, for the best half of the sky. Fig. 2(a) compares them at 100 GHz, near the peak of the CMB emission. This panel also shows for reference the difference between two angular power spectra differing by 2% of the Hubble constant. This does show that *foregrounds will indeed need be tamed*. Fig. 2(b) gives the *rms* fluctuation per Planck beam which follows by integrating in ℓ the power spectra of Fig. 2(a) multiplied by the beam profiles. It shows that measurements at a frequency close to 100 GHz minimise the global foreground contributions, which are then quite smaller than the CMB contribution.

Using this sky model, we can now forecast the accuracy of the component separations for different experimental set-ups, if we specify that the data would be analysed by optimal Wiener filtering [3,4]. Fig. 3 compares the results for WMAP and Planck. All the experimental characteristics used are those anticipated at the time when the instruments were proposed (and that have not evolved much, at least as far as temperature anisotropies are concerned). If the real sky does not depart too much from the model (as currently seems to be the case), and if the experiments deliver the promised performances, Fig. 3 indicates the great improvement in our knowledge of the CMB spectrum that one may expect in the coming years.

One should also mention that the great ability of Planck to allow cleaning the CMB from the contribution of foregrounds also means its great capacity in producing full sky maps of these foreground emissions themselves. These are 'secondary' goals of the mission which are in fact extremely interesting in their own right. Great progress in knowledge of the Interstellar Medium of our Galaxy, of the sub-mm emission of other galaxies, on the Sunyaev–Zeldovich emission from clusters is therefore anticipated. In fact, Planck-HFI will *open an essentially unexplored window on the Universe* (from 100 to 850 GHz), one of the rare remaining ones.

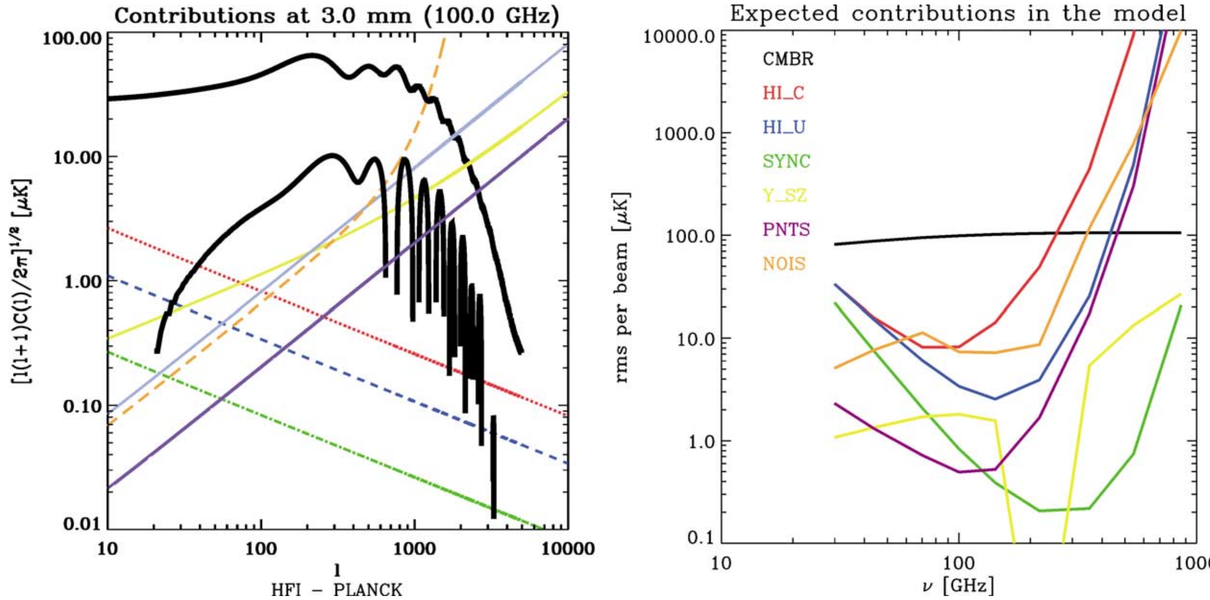


Fig. 2. Comparison of sources of microwave anisotropies: (a) (left) square root of the contribution to the variance per logarithmic interval, $\ell(\ell+1)C(\ell)$, of the various components at 100 GHz. From top to bottom at $\ell = 10\,000$, one finds estimates of the unresolved background from radio-sources, the SZ effect from clusters, the unresolved background from IR galaxies, the CMB (thick line) and the dust, free-free and synchrotron emissions of our galaxy. The other thick line shows the difference between two angular power spectra differing by only 2% of the Hubble constant. The dashed orange line that bends upward at large ℓ corresponds to the noise spectra of the HFI; (b) (right) various components in the Planck channels, using the same colour coding for the various components, but for noise which is now a solid orange. Adapted from [11] (the sensitivities have only slightly evolved since).

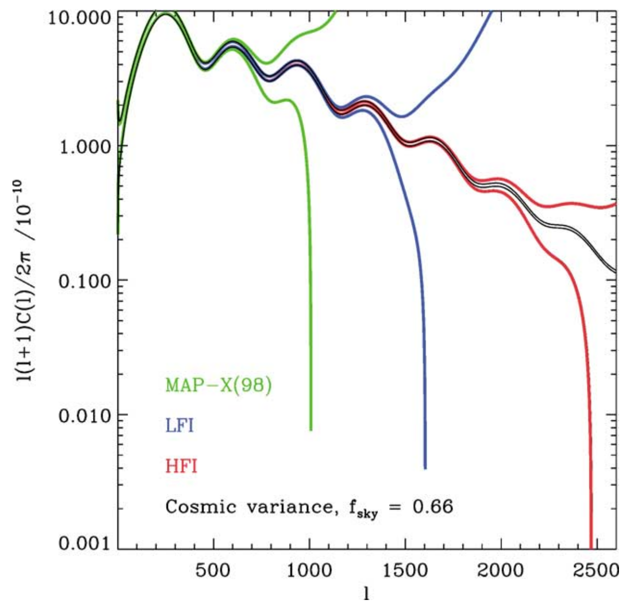


Fig. 3. Expected errors on the amplitudes of each mode individually. The thin central lines gives the target theory plus or minus the cosmic variance, for a retained coverage of 2/3 of the sky. The target theory used here is Lambda CDM (with $\Omega_b = 0.05$, $\Omega_{CDM} = 0.25$, $\Omega_\Lambda = 0.7$, $h = 0.5$). The colour lines gives the $\pm 1\sigma$ end of the error bar around the target model, when no band averaging was assumed. To estimate the height of a (square) band average of width $\Delta\ell$ around a given point ℓ, simply reduce the distance between the 1-σ contours at that ℓ by a factor $\sqrt{\Delta\ell}$. Adapted from [11].

3. Polarization

Another major source of information is the polarization of the CMB which is entirely generated at the Last Scattering Surface at $z \sim 1100$. It is convenient to decompose the polarization field into two scalar fields denoted E and B (to recall the similarity of their parity properties with that of electromagnetic fields). The power spectrum of the E part is expected to be about 10 times smaller than for the temperature field T, and the B part (which is only generated by tensor fluctuations) is even weaker. WMAP did not release so far a measurement of the EE power spectrum, but did provide a measurement of the T–E cross power spectrum (see Fig. 1(b)) which quantifies the expected correlation of the temperature and E field. This TE spectrum is easier to measure than the EE one owing to the much larger signal-to-noise of the temperature, and the cancellation of errors in cross-correlations.

However, if at WMAP sensitivities the TE and EE spectra carry equal weight (e.g., for constraining the reionisation history), at higher sensitivity all the information comes from EE. Fig. 4 shows the gain of sensitivity to be expected between the near-future ('Boomerang 2002' and WMAP at the end of the mission, left) and the Planck (right) experiments for the measurement of the E-type polarization. One computes a similar improvement for the cross-correlation spectrum. As shown in Fig. 5(a), Planck should also allow a measurement of the B spectrum, which is way out of reach of WMAP.

Such figures are only illustrative, however, since the actual precision reached will depend on how precisely the effect of astrophysical foreground fluctuations can be removed. The polarization signal is expected to be quite weaker than the temperature signal, by at least a factor of ten for E, and the polarization properties of the foregrounds are barely known at

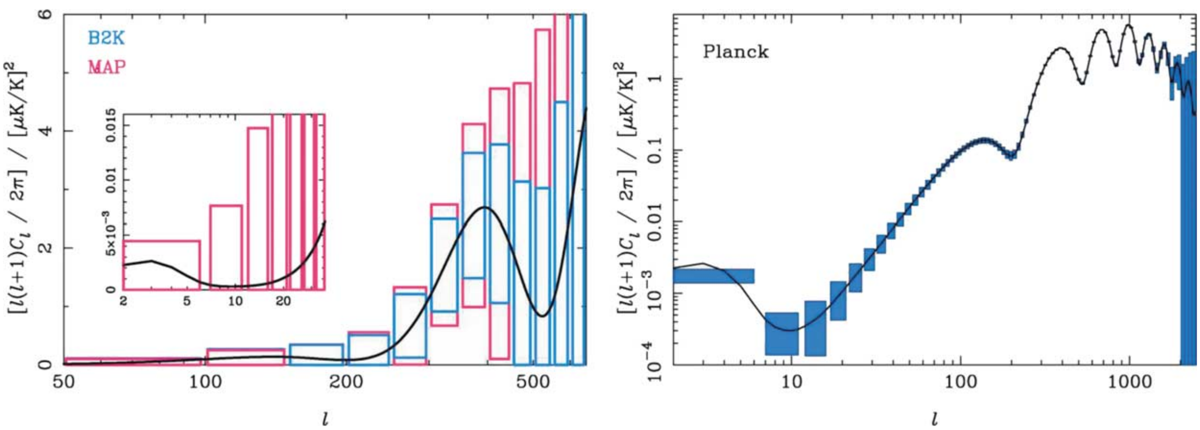


Fig. 4. Projected errors on the E type polarization power spectrum for the 2003 Boomerang flight and for WMAP on the left, and for Planck on the right (using the 142 and 217 GHz channels only, the others being assumed to be foreground tracers) [16].

(a) (b)

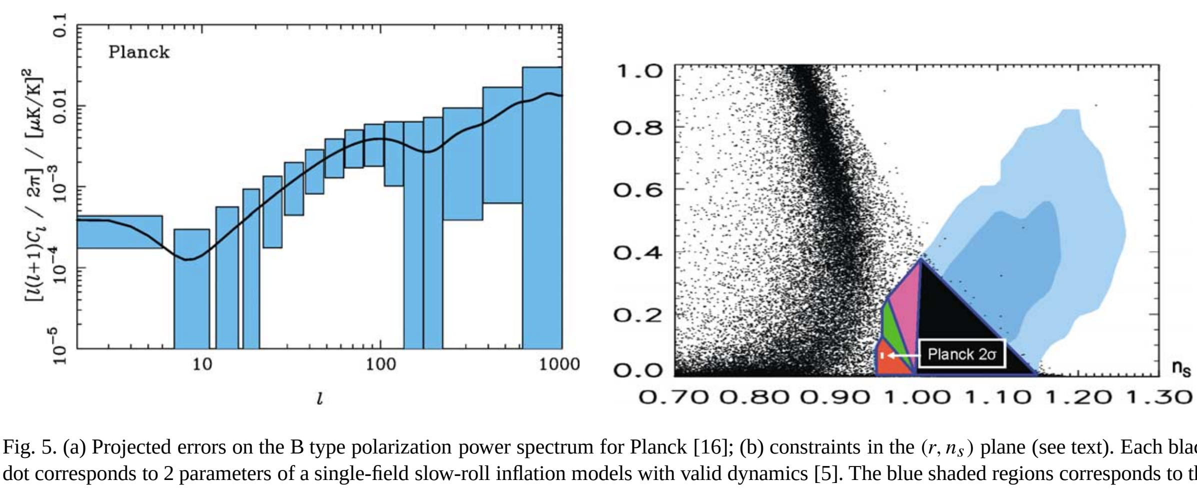


Fig. 5. (a) Projected errors on the B type polarization power spectrum for Planck [16]; (b) constraints in the (r, n_s) plane (see text). Each black dot corresponds to 2 parameters of a single-field slow-roll inflation models with valid dynamics [5]. The blue shaded regions corresponds to the 1 and 2σ constraints from WMAP [6], with the red green purple and black overlays each delimiting a class of inflation model (see text). The white area illustrate the type of accuracy expected from Planck namely $\Delta r \simeq \Delta n_s \simeq 0.02$ [12].

all. It is therefore quite difficult, if at all possible, to assess realistically to what extent foregrounds will decrease our ability at mapping the polarization of fluctuations at recombination.

Still, the increase in the precision of the determination of the $C(\ell)$'s will be large. In order to illustrate how this translates in terms of constraints on early Universe physics, Fig. 5(b) compares the current WMAP 2σ constraints (light blue area) versus that anticipated from Planck (white area), in the plane (r, n_S), where r stands for the amplitude of the primordial tensorial (gravitational wave) power spectrum in units of the amplitude of the primordial scalar (curvature) power spectrum, and n_S stands for the logarithmic slope of the primordial scalar spectrum (at some scale). Each black dot corresponds to a couple of reasonable inflation parameters [5]. In the region of overlap of the dot cloud with the WMAP-allowed region, the four colour overlays (red, green, purple and black) each correspond to a particular class of inflation models ranked by curvature of the potential [6]. As extraordinary as it is to start constraining those elusive but fundamental parameters, it remains that nearly every inflation model class is still alive today. But as the white area shows, the Planck data should allow 'zooming-in' on the parameters of the specific model which will be selected by the data (if there is such a model, i.e., if the spectra data does not force us to start considering a broader class than single field slow-roll models).

Before concluding this section, we should recall that the power spectra are only a first moment (the transform of a 2-pt angular correlation function). While enough to characterise a fully Gaussian distribution, deviations from Gaussianity *are* expected, albeit at a rather low level. Such a detection would reveal much about the mechanisms at work in the early Universe (if they are not residual systematics...).

4. Design of the Planck mission and instruments

As shown in the previous section, even with respect to the most recent results from the satellite WMAP, the increase of sensitivity that we are considering now for Planck will give a renewed view of the CMBA. In addition, the maps in the different bands and the possible separation of components from different physical origins would be important for galactic studies and for the knowledge of large scale structures in the universe. Going from the 35 µK noise level per 0.3 deg pixels of the WMAP maps to the expected 6 µK per 0.1 deg pixel now supposes an increase of the detector sensitivity by more than an order of magnitude, and an identical improvement in the control of other potential sources of noise. This is the goal of the Planck project, a medium mission of the scientific programme of the European Space Agency. The focal plane of the Planck satellite is shared between two instruments, the Low Frequency Instrument (LFI) and the High Frequency Instrument (HFI). The latter is based on the use of low temperature bolometers cooled by active cryogenic systems. It is developed by a large international collaboration under the leadership of French Institutes.

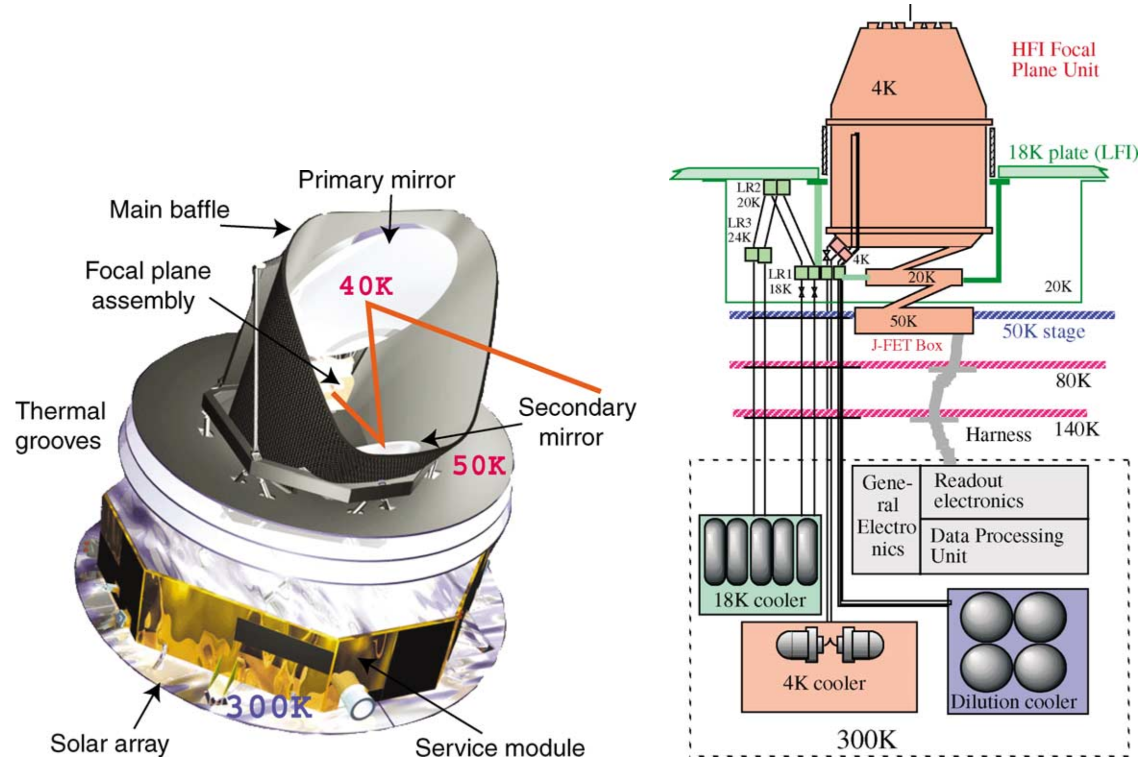
4.1. The Planck mission

The Planck mission has been designed to insure a proper rejection of straylight and to allow a passive cooling of the telescope and of the first stage of the focal plane down to 50 K. A halo orbit around the second Lagrangian point of the sun-earth system has been chosen, consistent with the need to be far from the Earth and the Moon, possible strong sources of straylight. The satellite is spinning at one revolution per minute with a spin axis nearly anti-solar. The instrument beam, at 85 deg from the spin axis, describes large circles on the sky that are slowly shifted so that the full sky is covered in half a terrestrial year. An optimised scanning strategy is essential for detecting, controlling and removing systematic effects which might affect the data. The Planck scanning strategy can be chosen to optimise the redundancy in the data by moving the spin axis by up to 10 deg from the antisolar direction.

For all practical temperatures of space instruments, thermal emission from optical elements contributes to the submillimeter radiation that reach the detectors, and therefore to the photon noise. This starts with the largest optical element, i.e., the telescope. In this frequency range, passively cooled telescopes are the proper solution if they are designed to minimize emissivity [7]. An off-axis design will provide the low emissivity and has the additional advantage that it provides low-level side-lobes thanks to the absence of any obstruction in the main beam. Fig. 6(a) shows the Planck satellite with its off-axis telescope and its characteristic V-shaped radiator. The expected temperature of the telescope is 40 K, which keeps its thermal emission to reasonable values at frequencies relevant for the CMB measurement.

4.2. The Low Frequency Instrument

The LFI instrument [8] is designed to produce images of the sky at 30, 44 and 70 GHz (see Table 1). The heart of the LFI instrument is a compact, 46-channel multifrequency array of differential receivers with ultra-low-noise amplifiers based on cryogenic indium phosphide (InP) high-electron-mobility transistors (HEMTs). Cooling to 20 K of the LFI front-end is achieved with a closed-cycle hydrogen sorption cryocooler which also provides 18 K precooling to the HFI [9]. This system ensures that



(a) (b)

Fig. 6. (a) Artist view of the Planck satellite; (b) schematic layout of the Planck cryogenic chain.

no vibration is exported to the detectors, a unique property of this kind of coolers which is very beneficial to Planck. A prototype of the Sorption Cooler is now working with the predicted cooling performances at the Jet Propulsion Laboratory (Pasadena). The radiometer design is driven by the need to suppress 1/f-type noise induced by gain and noise temperature fluctuations in the amplifiers, which would be unacceptably high for a simple total power system. A differential pseudo-correlation scheme is adopted, in which signals from the sky and from a blackbody reference load at about 4 K are differenced. Since the reference signal has been subject to the same gain variations in the two amplifier chains as the sky signal, the true sky power can be recovered. Insensitivity to fluctuations in the back-end amplifiers and detectors is realized by switching phase shifters at about 8 kHz synchronously in each amplifier chain. The rejection of 1/f noise, as well as the immunity to other systematic effects, is optimised if the two input signals are nearly equal. For this reason the reference loads are cooled to about 4 K by mounting them on the 4-K structure of the HFI. In addition, the effect of the residual offset (<2 K in nominal conditions) is compensated by introducing a gain modulation factor in the on-board processing which is used to balance the output signal.

Major progress in the performance of cryogenic InP HEMTs has been achieved since the beginning of the LFI development. The LFI prototype radiometers establish world-record low noise performances in the 30–70 GHz range and meet or surpass the LFI requirements both for noise, bandwidth and low power consumption. The LFI amplifiers have demonstrated noise temperatures <7.5 K at 30 GHz with 20% bandwidth.

To meet the challenging performance goals of the LFI requires not only great sensitivity and angular resolution, but also stringent control of systematic errors. The LFI goal is that the combination of all systematic effects on the final sky maps will be less than 3 μK per resolution element.

4.3. The High Frequency Instrument

We describe in more detail the Planck-HFI instrument which is the one reaching the ultimate sensitivity and which could do cosmologically meaningful polarization measurements over most of the sky, i.e., enabling Planck to be the reference third generation CMB experiment after COBE and WMAP.

The HFI [10] is a photometer instrument with 6 bands spanning the 100 to 857 GHz range using bolometric detectors at 100 mK (see Table 1). It includes the capability of measuring the polarization of the microwave emissions at several frequencies:

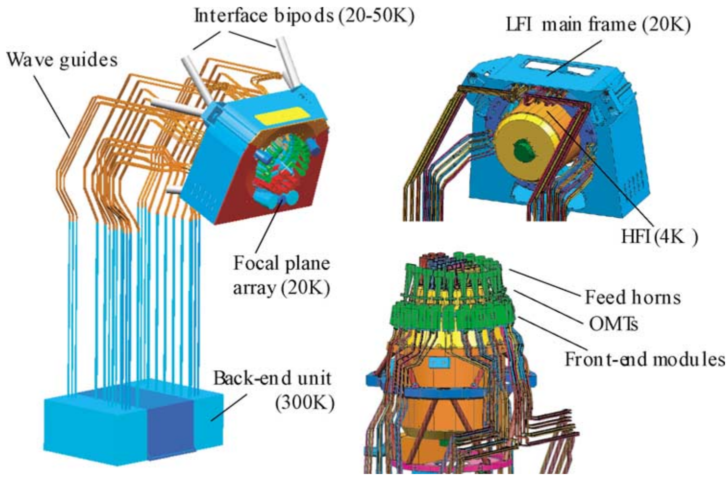


Fig. 7. The LFI radiometer array assembly (left), with details of the front-end unit (upper right) and of the frontend modules (lower right). The front-end unit is located at the focus of the Planck telescope.

143 and 217 GHz (best CMB channels) and 353 GHz to the map dust emission polarization. Measure of polarization at 100 GHz on HFI is waiting for approval (the 100 GHz LFI channels have been dropped due to funding constrains). Further, the number of detectors per frequency also provides increased sensitivity and improved redundancy. This leads to a focal plane layout of 48 detectors.

4.3.1. A new instrumental concept

The cosmological part of the scientific objectives has been taken as the basis for the instrument optimisation. The HFI sensitivity will be limited, in the CMB channels, by the statistical fluctuations of the CMB itself (photon noise), which makes it a kind of ultimate experiment.

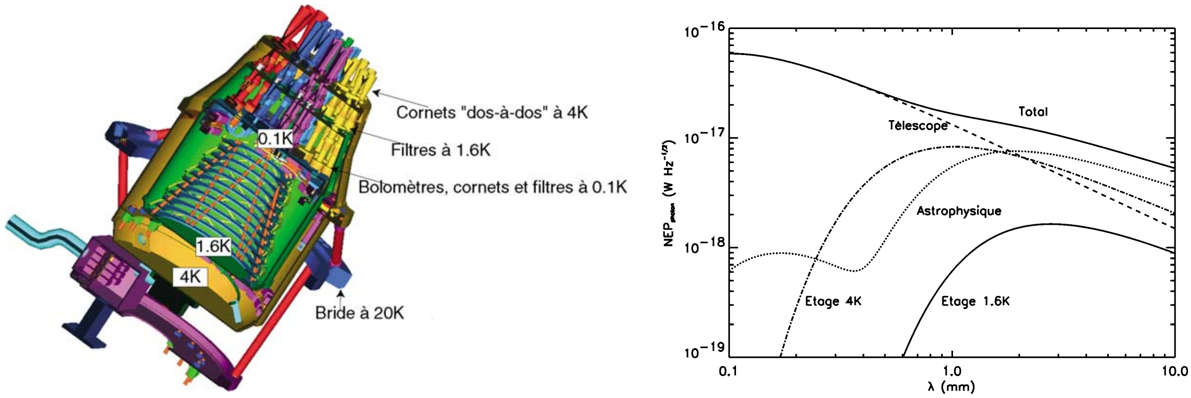
The design of this instrument was strongly conditioned by how it will be used. It proposes solutions in all domains that make it a consistent project, from its scientific goals to its detailed design. The following specific features were designed from the very beginning of the project and did not change much in the various versions it has known: thermal architecture with a passively cooled telescope, active cryogenics, sophisticated and compact optical design, use of spider-web bolometers at 0.1 K, new interference filters to select frequencies, total power readout electronics, scanning strategy based on six months sky coverage. These choices impacted the performance requirements on nearly every HFI subsystem. The inclusion of a number of new features was made necessary to reach a consistent design. When compared to previous projects, this makes Planck-HFI a conceptually new instrument serving an original mission concept.

4.3.2. Thermo-optical and cryogenic designs

The goal of building an instrument limited by the photon noise of the source in the CMB frequency range was a major driver for the design of the HFI and of the Planck satellite itself. Fig. 6 (a) and (b) gives an overview of the cryogenic chain, while Fig. 8(a) gives a view of the Russian doll architecture of the HFI. The HFI pre-cooling at 18 K is obtained thanks to the sorption cooler described in 4.2. A helium J–T cooler based on the use of frictionless mechanical pumps provides the cooling power at 4.5 K. The lowest temperature (0.1 K) is provided by the ^{3}He/^{4}He open loop dilution cooler, while the 1.6 K cooling capability is obtained by J–T expansion of the ^{3}He/^{4}He mixture. A prototype of this cooler has recently been successfully used for astronomical observations from the ground and with the balloon-borne experiment Archeops.

The corrugated horns at the entrance of the 4 K box ensure a well-controlled coupling of the detectors to the telescope and the sky. A set of filters, horns, and lenses determines the bandpass and leads the radiation to the detectors. This original optical scheme has shown a remarkably high optical efficiency as compared to more classical systems.

Elements in the optical path have temperatures distributed between 0.1 K and 4.5 K. The design was optimized, accounting for the cooling power available at various cryogenic stages and on the requirement that their own thermal emission is kept negligible with respect to the CMB flux. On the right part of Fig. 8, the contributions of the various optical elements to the photon noise are compared to the Brightness of the sky, showing that HFI is limited by the photon noise of the CMB for $\lambda \gtrsim 1$ mm.



(a) (b)

Fig. 8. (a) Planck-HFI cutaway; (b) contribution of the telescope and the optical elements at 1.6 K and 4 K to the total photon Noise Equivalent Power (equivalent to the total background power) at the HFI wavelengths. At wavelength greater than 1 mm, the photon noise is dominated by the CMB itself.

4.3.3. Bolometers

Bolometers cooled at 0.1 K are the most sensitive detectors for wide band photometry in the HFI spectral range. These detectors are sensitive to the heat deposited in an absorber by the incident radiation. Very low temperatures are required to obtain a low heat capacity giving a high sensitivity with a short enough thermal time constant. Scanning a 5 arcmin beam at 6 deg/s produces frequencies up to 100 Hz and thus times constants less than 2 ms are required for a proper measurement. At the same time, the intrinsic noise of the bolometer has to be less than the photon noise, which requires typically a Noise Equivalent Powers (NEPs) of the order of 10^{-17} W·Hz$^{-0.5}$ (cf. Fig. 8(b)). These requirements could possibly be met only by the spider-web 0.1 K bolometers developed in Caltech/JPL. Together with the development of zero gravity compatible dilution coolers, the existence of such detectors was one of the triggers of the Planck-HFI conception. The special point in spider-web bolometers is that the radiation absorber is made of a grid whose impedance is matched with that of vacuum. Among other advantages these detectors are much less sensitive to ionizing radiation that conventional bolometers. Polarization sensitive bolometers were developed especially for this project. They are very similar to spider-web bolometers except for the grid that consists mainly of parallel resistive wires that absorb only the polarized component with electrical field parallel to the wires. A second absorber with perpendicular wires detects the other component. All the optics has to be consistent with this design. In particular, it has to properly keep the polarization of the transmitted wave. The bolometers of the qualification model have been fabricated and proven to meet or exceed the required performances.

The readout electronics are based on modulated bias and low noise lock-in amplifiers. They are able to transmit signals from DC up to 100 Hz, corresponding to the full range of angular frequencies relevant for the interpretation of CMB anisotropy. The data are then compressed to an average flow of about 50 kbits per second for transmission to the ground.

4.3.4. Expected sensitivities

Table 1 gives the *goal* values of the HFI sensitivity. The HFI has been optimized by assuming that the total instrument noise was twice the total photon noise produced by the sky and the instrument itself, i.e., mainly the telescope. At the same time, additional simulations have tested the robustness of this design. It has been shown, for example, that the failure of any channel, excepted for the 217 GHz, would have really small consequences. It has also been shown that a degradation of a factor 2 of the sensitivity would not have a major impact on the core of the science objectives, i.e., the derivation of cosmological parameters from the CMB maps. This particular conclusion results from the fact that it is predicted that the main source of uncertainty will come from the imperfect subtraction of the contaminating foregrounds, and not from the ultimate sensitivity of the experiment. It was therefore considered as acceptable for the core science objectives to actually reach a sensitivity twice worse than Table 1, which, in the Planck-HFI vocabulary, defines the current *requirement* (rather than the goal) on sensitivity at mission level. While the project was developing, a better knowledge was acquired on all elements of this fundamentally new design, and the following philosophy was settled on and maintained: all elements had to be designed to be at least able to give the sensitivity of Table 1, that became the expected average noise (EAN). A goal was set at system level to do better than the EAN. A monitoring of all sources of noise and of all parameters related to sensitivity is constantly performed. Everything indicates today that the HFI sensitivity will be equal to the published EAN or better. In particular, the initially most unknown of the parameters, the efficiency of the optical system, is now known to be most probably equal to its highest expected value.

5. Conclusions

The field of CMB observations is fast changing in many respects. Second generation experiments begin to give spectacular results and will keep doing so in the coming years. These experiments measure the CMB at the best frequencies where foregrounds are minimal. In fact, their sensitivity will not require more than a rough subtraction of the dominant foreground.

High accuracy measurements of the intensity and of the polarization will require the observation and removal of all the foregrounds. This, in turn, will be possible only if the physics of these emissions is understood well enough. For extragalactic point sources and galactic dust emission many questions are still open and will demand work before the type of foreground subtraction needed for Planck can be done. We can mention the redshift evolution of infrared galaxies or the galactic dust polarization as examples of such questions.

In summary, the Planck HFI has been designed to be the ultimate experiments to map CMB temperature fluctuations. Its sensitivity will be limited by the photon noise of the CMB radiation itself. Planck HFI will also permit very precise measurement of the polarization of the CMB fluctuations that may even allow detecting the direct imprint of the primordial gravitational wave background. The Planck satellite will be launched in 2007 and a rich scientific harvest is eagerly anticipated.

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References

[1] F.R. Bouchet, F. Gispert, R. Boulanger, J.-L. Puget, in: F.R. Bouchet, R. Gispert, B. Guiderdoni, J. Trân Thanh Vân (Eds.), Microwave Background Anisotropies, Proceedings of the 16th Moriond Astrophysics Meeting, held in Les Arcs, France, March 16–23, 1996, Frontières, 1997, pp. 481–502.
[2] Planck-HFI Consortium AAO, Proposal submitted in response to the Annoucement of Opportunity of ESA, 1998.
[3] F.R. Bouchet, R. Gispert, J.-L. Puget, in: E. Dwek (Ed.), Unveiling the Cosmic Infrared Background; held in 1995 in College Park, MD, AIP Conf. Proc. 348 (1996) 255–268.
[4] M. Tegmark, G. Efstathiou, MNRAS 281 (1996) 1297.
[5] W.H. Kinney, PRD 66 (2002) 83508.
[6] H.V. Peiris, E. Komatsu, L. Verde, D.N. Spergel, C.L. Bennett, M. Halpern, G. Hinshaw, N. Jarosik, A. Kogut, M. Limon, S. Meyer, L. Page, G.S. Tucker, E. Wollack, E.L. Wright, Astrophys. J. (2003), in press, astro-ph/0302225.
[7] J.M. Lamarre, F.-X. Désert, T. Kirchner, Space Science Reviews 74 (1995).
[8] M. Bersanelli, N. Mandolesi, Astroph. Lett. & Comm. 37 (2000) 171–180.
[9] L.A. Wade, P. Bhandari, R.C. Bowman, C. Paine, G. Morgante, A. Lindensmith, D. Crumb, M. Prina, R. Sugimura, D. Rapp, Adv. Cryogenic Eng. 45 (2000) 499–506.
[10] J.M. Lamarre, J.L. Puget, M. Piat, P.A.R. Ade, A. Lange, A. Benoit, P. De Bernardis, F.R. Bouchet, J. Bock, F.X. Désert, R. Emery, M. Giard, B. Maffei, A. Murphy, J.P. Torre, R. Bhatia, R. Sudiwala, V. Yourchenko, Conf. 4850, SPIE Symposium, 22–28 August 2002, Waikoloa, Hawaii, USA.
[11] F.R. Bouchet, R. Gispert, New Astronomy 4 (1999) 443–479.
[12] W.H. Kinney, PRD 58 (1998) 123506.
[13] A. Kogut, D.N. Spergel, C. Barnes, C.L. Bennett, M. Halpern, G. Hinshaw, N. Jarosik, M. Limon, S.S. Meyer, L. Page, G.S. Tucker, E. Wollack, E.L. Wright, Astrophys. J. (2003), in press, astro-ph/0302213.
[14] J.M. Kovac, E.M. Leitch, C. Pryke, J.E. Carlstrom, N.W. Halverson, W.L. Holzapfel, Nature 420 (2002) 772.
[15] A. de Oliveira-Costa, M. Tegmark, M. Zaldarriaga, D. Barkats, J.O. Gundersen, M.M. Hedman, S.T. Staggs, B. Winstein, PRD 67 (2003) 23003.
[16] Planck Consortia, The scientific Program of Planck, 2004, in preparation.