Mem. S.A.It. Suppl. Vol. 19, 249

Memorie della
Supplementi

The Planck mission

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Abstract. This paper provides an overview of the ESA *Planck* mission and its scientific promises. *Planck* is equipped with a 1.5–m effective aperture telescope with two actively-cooled instruments observing the sky in nine frequency channels from 30 GHz to 857 GHz: the Low Frequency Instrument (LFI) operating at 20 K with pseudo-correlation radiometers, and the High Frequency Instrument (HFI) with bolometers operating at 100 mK. After the successful launch in May 2009, *Planck* has already mapped the sky twice (at the time of writing this review) with the expected behavior and it is planned to complete at least two further all-sky surveys. The first scientific results, consisting of an Early Release Compact Source Catalog (ERCSC) and in about twenty papers on instrument performance in flight, data analysis pipeline, and main astrophysical results, will be released on January 2011. The first publications of the main cosmological implications are expected in 2012.

1. Introduction

In 1992, the Cosmic Background Explorer (*COBE*) team announced the discovery of intrinsic temperature fluctuations in the cosmic microwave background radiation (CMB) on angular scales greater than 7° and at a level of a few tens of μK (Smoot et al. 1992). One year later two spaceborne CMB experiments were proposed to the European Space Agency (ESA) in the framework of the Horizon 2000 Scientific Programme: the Cosmic Background Radiation Anisotropy Satellite (COBRAS; Mandolesi et al. (1994)), an array of receivers based on High Electron Mobility Transistor (HEMT) amplifiers; and the SAtellite for Measurement of Background Anisotropies (SAMBA), an array of detectors based on bolometers (Tauber et al. 1994). The two proposals were accepted for an assessment study with the recommendation to merge. In 1996, ESA selected a combined mission called COBRAS/SAMBA, subsequently renamed *Planck*, as the third Horizon 2000 Medium-Sized Mission.

The *Planck* CMB anisotropy probe[1], the first European and third generation mission after *COBE* and *WMAP* (Wilkinson Microwave Anisotropy Probe[2]), represents the state-of-the-art in precision cosmology today (Tauber et al. 2010; Bersanelli et al. 2010; Lamarre et al. 2010). The *Planck* payload (telescope instru-

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[1] *Planck* (http://www.esa.int/Planck) is a project of the European Space Agency - ESA - with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

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

ment and cooling chain) is a single, highly integrated spaceborne CMB experiment. *Planck* is equipped with a 1.5–m effective aperture telescope with two actively-cooled instruments that will scan the sky in nine frequency channels from 30 GHz to 857 GHz: the Low Frequency Instrument (LFI) operating at 20 K with pseudo-correlation radiometers, and the High Frequency Instrument (HFI; Lamarre et al. 2010) with bolometers operating at 100 mK. The coordinated use of the two different instrument technologies and analyses of their output data will allow optimal control and suppression of systematic effects, including discrimination of astrophysical sources. All the LFI channels and four of the HFI channels will be sensitive to the linear polarisation of the CMB. A summary of the LFI and HFI performances is reported in Table 1.

The constraints on the thermal behaviour, required to minimize systematic effects, dictated a *Planck* cryogenic architecture that is one of the most complicated ever conceived for space. Moreover, the spacecraft has been designed to exploit the favourable thermal conditions of the L2 orbit. The thermal system is a combination of passive and active cooling: passive radiators are used as thermal shields and pre-cooling stages, while active cryocoolers are used both for instrument cooling and precooling. The cryochain consists of various subsystems (Collaudin & Passvogel 1999). The *Planck* H_2 Sorption Cooler Subsystem (SCS) is the first long-duration system of its kind to be flown on a space platform.

Planck is a spinning satellite. Thus, its receivers will observe the sky through a sequence of (almost great) circles following a scanning strategy (SS) aimed at minimizing systematic effects and achieving all-sky coverage for all receivers. The spin axis is repointed every ~ 48 minutes with a constant spacing of $2'$. The *baseline* SS (Maris et al 2006a) adopts a cycloidal modulation of the spin axis, i.e. a precession around a nominal antisolar direction with a semiamplitude cone of $7.5°$ and a 6-month period. Thus, all *Planck* receivers will cover the whole sky, the mission operational constraints are satisfied, sharp gradients in the pixel hit count are avoided (Dupac & Tauber 2005), and the results of map-making are improved, particularly for polarisation (Ashdown et al. 2007).

The current mission lifetime is of about 28 months, which will allow us to perform more than 4 complete sky surveys.

The data analysis, its scientific exploitation, and the core cosmology programme of Planck are mostly carried out by two core teams (one for LFI and one for HFI), working in close connection with the Data Processing Centres (DPCs), and closely linked to the wider *Planck* scientific community, consisting of the LFI, HFI, and Telescope consortia, which are organized into various working groups. *Planck* is managed by the ESA *Planck* science team.

Planck will open a new era in our understanding of the Universe and of its astrophysical structures (Planck Collaboration 2006). To achieve these ambitious goals an extremely accurate and efficient data analysis and a careful separation of CMB and astrophysical emissions is demanded.

2. Scientific data analysis and component separation

The process of the analysis of *Planck* data must be capable of reducing the data volume by several orders of magnitude with minimal loss of information. The *Planck* data are calibrated using the CMB dipole and its modulation during the year (except for the *Planck* highest frequencies). Other fundamental steps are the flagging of the raw data and the beam reconstruction (Sandri et al. 2010; Bersanelli et al. 2010; Maffei et al. 2010; Lamarre et al. 2010). The step following the production of calibrated timelines is the creation of calibrated frequency maps. For each sample, pointing information (ordered in time) associated to the data timeline identify a direction in the sky and the corresponding pixel in the adopted HEALPix pixelisation scheme (Gorski et al. 2005). Timeline-specific instrumental effects that are not scan-synchronous are reduced in magnitude when projected from time to pixel space (see e.g., Mennella et al. 2002). Several map-making algorithms have been proposed

Table 1. *Planck* performances. The average sensitivity, δT/T, per FWHM^2 resolution element (FWHM is reported in arcmin) is given in CMB temperature units (i.e. equivalent thermodynamic temperature) for 28 months of integration. The white noise (per frequency channel for LFI and per detector for HFI) in 1 sec of integration (NET, in μK $\cdot \sqrt{s}$) is also given in CMB temperature units. The other used acronyms are: DT = detector technology, N of R (or B) = number of radiometers (or bolometers), EB = effective bandwidth (in GHz). Adapted from Mandolesi et al. (2010) and Lamarre et al. (2010).

LFI			
Frequency (GHz)	30	44	70
InP DT	MIC	MIC	MMIC
FWHM	33.34	26.81	13.03
N of R (or feeds)	4 (2)	6 (3)	12 (6)
EB	6	8.8	14
NET	159	197	158
δT/T [μK/K] (in T)	2.48	3.82	6.30
δT/T [μK/K] (in P)	3.51	5.40	8.91

HFI		
Frequency (GHz)	100	143
FWHM in T (P)	(9.6)	7.1 (6.9)
N of B in T (P)	(8)	4 (8)
EB in T (P)	(33)	43 (46)
NET in T (P)	100 (100)	62 (82)
δT/T [μK/K] in T (P)	2.1 (3.4)	1.6 (2.9)
Frequency (GHz)	217	353
FWHM in T (P)	4.6 (4.6)	4.7 (4.6)
N of B in T (P)	4 (8)	4 (8)
EB in T (P)	72 (63)	99 (102)
NET in T (P)	91 (132)	277 (404)
δT/T [μK/K] in T (P)	3.4 (6.4)	14.1 (26.9)
Frequency (GHz)	545	857
FWHM in T	4.7	4.3
N of B in T	4	4
EB in T	169	257
NET in T	2000	91000
δT/T [μK/K] in T	106	4243

to produce sky maps in total intensity (Stokes I) and linear polarization (Stokes Q and U). Provided that the knee frequency is not too high, hybrid algorithms can achieve GLS accuracy at a fraction of the computational demand (Cantalupo et al. 2010; Ashdown et al. 2007). Map-making algorithms provide the correlation (inverse covariance) matrix of the map estimate that they produce (Keskitalo et al. 2010); this is of extreme importance for the accurate characterization of the low multipoles of the CMB (Keskitalo et al. 2010; Gruppuso et al. 2009). At high resolution this computation, though feasible, is impractical, and in this case just the 3x3 noise covariance for each pixel (correlation between T,Q,U) is provided.

A key step of the *Planck* data analysis is the separation of astrophysical from cosmological components. For cosmological purposes, the most sensitive channels are between 70 GHz and 143 GHz. However, the other channels are essential for achieving the accurate separation of the CMB from astrophysical emissions, particularly for polarization, maximize the effective sky area used in the analysis. A variety of methods have been developed (**?**). Regarding the extraction of compact objects, the two DPCs are supplied with non blind codes by exploiting non-*Planck* catalogues and blind codes filtering *Planck* maps with optimal functions (wavelets) capable of recognizing beam-like patterns Lopez-Caniego et al. (2006). Regarding diffuse emission, several tools that belong to three main categories are available: ILC (internal linear combination), ITF (internal template fitting), parametric methods. The goal for such tools is also that of propagating instrumental and foreground uncertainties to provide an accurate description of the separated components, both at high multipoles and at low multipoles, exploiting the full noise covariances. This requirement is fundamental to carry on the further steps of the analysis.

The extraction of statistical information from the CMB usually proceeds by means of correlation functions. Since the CMB field is Gaussian to a large extent, assuming rotational invariance, most of the information is compressed in the two-point correlation function or equivalently in its reciprocal representation in spherical harmonics space, the angular power spectrum (APS), C_ℓ (see e.g., Scott & Smoot 1998). For an ideal experiment, the estimated APS could be directly compared to a Boltzmann code [3] prediction to constrain the cosmological parameters. However, in the case of incomplete sky coverage and realis-

[3] http://camb.info/

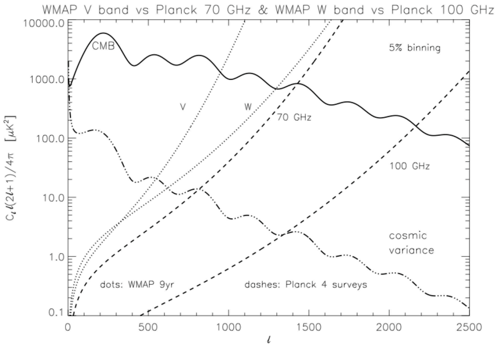

Fig. 1. CMB temperature anisotropy APS (solid line) compatible with *WMAP* data is compared to *WMAP* (V and W band) and *Planck* (at 70 and 100 GHz) sensitivity, assuming subtraction of the noise expectation, for the whole guaranteed mission duration (28 months). The plot shows separately the cosmic variance (three dot-dashes) and the instrumental noise assuming always a multipole binning of 5%. Regarding sampling variance, an all-sky survey is assumed for simplicity. The use of the CAMB code is acknowledged (see footnote 3).

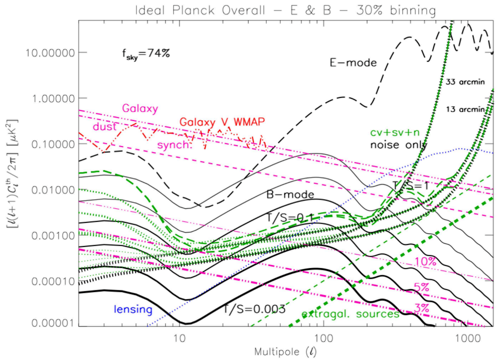

Fig. 2. CMB E polarisation modes (black long dashes) compatible with *WMAP* data and CMB B polarisation modes (black solid lines) for different tensor-to-scalar ratios of primordial perturbations ($r \equiv T/S = 1, 0.3, 0.1, 0.03, 0.01, 0.003$, at increasing thickness) are compared to *Planck* overall sensitivity to the APS, assuming the noise expectation has been subtracted. The plots include cosmic and sampling variance plus instrumental noise (green dots for B modes, green long dashes for E modes, labeled with cv+sv+n; black thick dots, noise only) assuming a multipole binning of 30% and a smoothing to two different FWHM corresponding to LFI 30 and 70 GHz. The B mode induced by lensing (blue dots) is also shown for comparison. We display also the comparison with Galactic and extragalactic polarised foregrounds at a reference frequency of 70 GHz. Galactic synchrotron (purple dashes) and dust (purple dot-dashes) polarised emissions produce the overall Galactic foreground (purple three dot-dashes). *WMAP* 3-yr power-law fits for uncorrelated dust and synchrotron have been used. For comparison, *WMAP* 3-yr results derived directly from the foreground maps using the HEALPix package (Gorski et al. 2005) are shown: power-law fits provide (generous) upper limits to the power at low multipoles. Residual contamination levels by Galactic foregrounds (purple three dot-dashes) are shown for 10%, 5%, and 3% of the map level, at increasing thickness. See also the text.

tic noise a more thorough analysis is necessary. The likelihood function for a Gaussian CMB sky can be easily written for constraining models and data. The direct evaluation of this function, however, poses intractable computational issues. Fortunately, only the lowest multipoles require exact treatment, realized with different methods (Jewell et al. 2004; Wandelt et al. 2004). At high multipoles, where the likelihood function cannot be evaluated exactly, a wide range of effective, computationally affordable approximations exist (see e.g., Hamimeche & Lewis 2008 and Rocha et al. 2009 and references therein). The low and high ℓ approaches to APS estimation will be joined into a hybrid procedure, pioneered by Efstathiou (2004).

The size and complexity of *Planck* data analysis will require daunting computational resources. The accurate characterization of the scientific results and error propagation will be achieved by means of a massive use of Monte Carlo simulations. A number of worldwide distributed supercomputer centers will support the DPCs in this activity.

3. Cosmology with *Planck*

The quality of the recovered APS is a good predictor of the efficiency of extracting cosmological parameters by comparing the theoretical predictions of Boltzmann codes. Neglecting systematic effects (and correlated noise), the sensitivity of a CMB anisotropy experiment to C_ℓ, at each multipole ℓ, is summarized by the equation (Knox 1995) $\delta C_\ell / C_\ell \simeq \sqrt{2/[f_{\rm sky}(2\ell+1)]}\left[1 + A\sigma^2/(NC_\ell W_\ell)\right]$, where A is the size of the surveyed area, $f_{\rm sky} = A/4\pi$, σ is the rms noise per pixel, N is the total number of observed pixels, and W_ℓ is the beam window function. For a symmetric Gaussian beam, $W_\ell = \exp(-\ell(\ell+1)\sigma_{\rm B}^2)$, where $\sigma_{\rm B} = {\rm FWHM}/\sqrt{8 \ln 2}$ defines the beam resolution. Even for $\sigma = 0$, the accuracy in the APS is limited by so-called cosmic and sampling variance, reducing to pure cosmic variance in the case of all-sky coverage, that are particularly important at low ℓ.

Figures 1 compares *WMAP* and *Planck* sensitivity to the CMB temperature APS, C_ℓ, at similar frequency bands. The figure shows how the multipole region, where cosmic variance dominates over instrumental sensitivity, moves to much higher multipoles in the case of *Planck*.

As well as the temperature APS, *Planck* can measure polarisation anisotropies up to 353 GHz. Fig. 2) shows *Planck* sensitivity to the 'E' and 'B' polarisation modes. Note that the cosmic and sampling (74% sky coverage, as in WMAP polarization analysis) variance implies a dependence of the overall sensitivity at low multipoles on r (the green lines refer to the same r values as above), which is relevant to the parameter estimation; instrumental noise only determines the capability of detecting the B mode. We considered 28 months of integration as in Fig. 1 (but for the case of a smoothing to the LFI 70 GHz the upper curve displays also the case of 15 months of integration). Clearly, foreground is more important for measurements of polarisation than for measurements of temperature. In the *WMAP* V band and the LFI 70 GHz channels the polarised foreground is minimal (at least considering a very large fraction of the sky and for the range of multipoles already explored by *WMAP*). The figure reports estimates of the residual contribution of unsubtracted extragalactic sources, $C_\ell^{\rm res,PS}$ and the corresponding uncertainty, $\delta C_\ell^{\rm res,PS}$ (plotted as thick and thin green dashes). The Galactic foreground dominates over them and also over the CMB B mode and also the CMB E mode by up to multipoles of several tens. However, foreground subtraction at an accuracy of 5−10% of the map level is enough to reduce residual Galactic contamination to well below both the CMB E mode and the CMB B mode for a wide range of multipoles for $r = T/S \simeq 0.3$ (here r is defined in Fourier space). If we are able to model Galactic polarised foregrounds with an accuracy at the several percent level, then the main limitation will come from instrumental noise. Clearly, a more accurate recovery of the polarisation modes will be possible from the exploitation of the *Planck* data at all frequencies. As shown in Fig. 2, values of $r \gtrsim 0.05$ are potentially achievable with *Planck*.

Planck will permit to significantly improve the determination of the cosmological parameters that are expected to be obtained with a relative error of the order of 1% or lower (see Fig. 5 of Mandolesi et al. (2010) where a detailed forecast is provided) opening a new phase in our understanding of cosmology.

Moreover, *Planck* will test the Gaussianity of the CMB anisotropies usually assumed by simple cosmological models. However, important information may come from mild deviations from Gaussianity (see e.g., Bartolo et al. 2004 for a review). *Planck* data will either provide the first true measurement of non-Gaussianity (NG) in the primordial curvature perturbations, or tighten the existing constraints (based on *WMAP* data, see http://lambda.gsfc.nasa.gov/) by almost an order of magnitude. The standard way to parameterize primordial non-Gaussianity involves the parameter $f_{\rm NL}$, which is typically small. A positive detection of $f_{\rm NL} \sim 10$ would imply that all standard single-field slow-roll models of inflation are ruled out. In contrast, an improvement to the limits on the amplitude of $f_{\rm NL}$ will allow one to strongly reduce the class of nonstandard inflationary models allowed by the data.

In addition, *Planck* will provide independent investigations of the large-scale anomalies suspected in the WMAP temperature data that could be indicative of new (and fundamental) physics beyond the concordance model or simply the residuals of imperfectly removed astrophysical foreground (see also (Maris et al. 2010)) or systematic effects. *Planck* will extend those investigations to polarization maps, observing the sky with a totally different scanning strategy with respect to WMAP, which represents a further benefit from the point of view of systematic effects analysis. Although the CMB anisotropy pattern obtained by *WMAP* is largely consistent with the concordance ΛCDM model, there are some interesting and curious deviations from it: lack of power on large scales Copi et al. (2007, 2009), hemispherical asymmetries (Eriksen et al. 2004a,b; Hansen et al. 2004; Paci et al. 2010), unlikely alignments of low multipoles (Tegmark et al. 2003; Copi et al. 2004; Schwarz et al. 2004; Weeks 2004; Land & Magueijo 2005; Copi et al. 2007; Abramo et al. 2006; Wiaux et al. 2006; Vielva et al. 2007; Gruppuso & Burigana 2009; Gruppuso & Gorski 2010), a localized non-Gaussian behaviour in the southern hemisphere, usually called Cold Spot Vielva et al. (2004); Cruz et al. (2005), an anomalous excess of signal in the ecliptic plane Diego et al. (2010), TT parity asymmetry Kim & Naselsky (2010a,b); Gruppuso et al. (2011).

4. Astrophysics with *Planck*

Planck will carry out an all-sky survey of the fluctuations in Galactic emission at its nine frequency bands. The HFI channels at $\nu \geq 100$ GHz will provide the main improvement with respect to *COBE* characterizing the large-scale Galactic dust emission which is still poorly known, particularly in polarisation, while LFI will provide crucial information about the low frequency tail of this component. The LFI frequency channels, in particular those at 30 GHz and 44 GHz, will be relevant to the study of the diffuse, significantly polarised synchrotron emission and the almost unpolarised free-free emission.

Results from *WMAP*'s lowest frequency channels inferred an additional contribution, probably correlated with dust (see Dobler et al. (2009) and references therein). While a model with complex synchrotron emission pattern and spectral index cannot be excluded, several interpretations of microwave (see e.g. Hildebrandt et al. 2007; Bonaldi et al. 2007) and radio (La Porta et al. 2008) data, and in particular the ARCADE 2 results (Kogut et al. 2009), seem to support the identification of this anomalous component as spinning dust (Drain et al. 1998; Laziarian & Finkbeiner 2003).

Another interesting component that will be studied by *Planck* data is the so-called "haze" emission in the inner Galactic region, possibly generated by synchrotron emission from relativistic electrons and positrons produced in the annihilations of dark matter particles (see e.g., Hooper et al. 2007; Cumberbatch et al. 2009; Hooper et al. 2008 and references therein).

Furthermore, the full interpretation of the Galactic diffuse emissions in *Planck* maps will benefit from a joint analysis with both radio and far-IR data. The ultimate goal of these studies is the development of a consistent Galactic 3D model, which includes the various components of the ISM, and large and small scale magnetic fields (see e.g., Waelkens et al. 2009), and turbulence phenomena (Cho & Lazarian 2003).

While having moderate resolution and being limited in flux to a few hundred mJy, *Planck* will also provide multifrequency, all-sky information about many classes of discrete Galactic sources, having a chance to observe some Galactic micro-blazars (such as e.g., Cygnus X-3) in a flare phase.

Finally, *Planck* will provide unique information for modelling the emission from moving objects and diffuse interplanetary dust in the Solar System (Cremonese et al. 2002; Maris & Burigana 2009; Maris et al. 2006b).

The higher sensitivity, angular resolution, and frequency coverage of *Planck* compared to *WMAP* will allow us to obtain much richer samples of extragalactic sources at mm and sub-mm wavelengths (Herranz et al. 2009).

Planck will allow us to obtain good statistics for different subpopulations of sources, some of which are not (or only poorly) represented in the *WMAP* sample. Also, interesting will be the synergy with high energy astrophysics observations, e.g. with *Fermi Gamma-ray Space Telescope* (Abdo et al. 2009; Fermi/LAT Collaboration 2009).

One noteworthy example is the *Planck* contribution to the astrophysics of clusters. *Planck* will detect $\approx 10^3$ galaxy clusters out to redshifts of order unity by means of their thermal Sunyaev-Zel'dovich effect (Leach et al. 2008; Bartlett et al. 2008). This sample will be extremely important for understanding both the formation of large-scale structure and the physics of the intracluster medium. *Planck*, supplemented by ground-based, follow-up observations planned by the *Planck* team, will allow, in particular, accurate correction for the contamination by radio sources (mostly due to the high quality of the LFI channels) and dusty galaxies (HFI channels), either associated with the clusters or in their foreground/background (Lin et al. 2009).

5. Conclusion

After the successful launch in May 2009, *Planck* has already mapped the sky twice (at the time of writing this review) with the expected behavior and it is planned to complete at least two further all-sky surveys. The release of the first scientific results is expected for January 2011 and will consists of an Early Release Compact Source Catalog (ERCSC) and in about twenty papers on instrument performance in flight, data analysis pipeline, and main astrophysical results. The first publications of the main cosmological implications are expected in 2012.

Acknowledgements. We acknowledge the support by the ASI/INAF Agreement I/072/09/0 for the *Planck* LFI Activity of Phase E2.

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