Observational and modelling programs for plasma astrophysics

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An overview of 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.

Keywords. Cosmology, cosmic microwave background, space missions

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 (Smooth *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†, the first European and third generation mission after *COBE* and *WMAP* (Wilkinson Microwave Anisotropy Probe‡), represents the state-of-the-art in precision cosmology today (Tauber *et al.*, 2009; Bersanelli *et al.*, 2010; Lamarre *et al.*, 2010). The *Planck* payload (telescope instrument 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

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

‡ http://lambda.gsfc.nasa.gov/

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. Note that *Planck* is sensitive to polarization up to the 353 GHz. 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, active cryocoolers are used both for instrument cooling and pre-cooling (Collaudin & Passvogel, 1999). *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 (Dupac & Tauber, 2005; Ashdown *et al.*, 2007).

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, 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 (Tauber *et al.*, 2010) an extremely accurate and efficient data analysis and a careful separation of CMB and astrophysical emissions is demanded.

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

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2. From data analysis to cosmology and astrophysics

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, maximizing the effective sky area used in the analysis. The extraction of compact objects, is pursued with non-blind and blind codes (Lopez-Caniego *et al.*, 2006). To deal with the diffuse emission a variety of methods have been developed (Leach *et al.*, 2008) like: 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, a fundamental ingredient to carry on the further steps of the analysis. 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 the angular power spectrum (APS), C_ℓ (Scott & Smoot, 1998). For an ideal experiment, the estimated APS could be directly compared to a Boltzmann code (http://camb.info/) prediction to constrain the cosmological parameters. In the case of incomplete sky coverage and realistic noise a more thorough analysis is necessary (Jewell *et al.*, 2004; Wandelt *et al.*, 2004; Hamimeche & Lewis, 2008; Rocha *et al.*, 2009; Efstathiou, 2004).

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)

$$\delta C_\ell / C_\ell \simeq \sqrt{2/[f_{\rm sky}(2\ell+1)]}\,\left[1 + A\sigma^2/(N C_\ell W_\ell)\right]$$

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 $\sigma_{\rm B} = {\rm FWHM}/\sqrt{8\ln 2}$. Even for $\sigma = 0$, the accuracy in the APS is limited by the so-called cosmic and sampling variance, particularly relevant at low ℓ.

Higher sensitivity of *Planck* will permit to observe up to about the 7th or 8th peak of APS of CMB temperature anisotropies, i.e. 4 more peaks with respect to *WMAP*. As well as the temperature APS, *Planck* can measure polarisation anisotropies up to 353 GHz. Fig. 1 shows *Planck* sensitivity to the 'E' and 'B' polarisation modes. Note that the cosmic and sampling 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 (but for the case of a smoothing to the LFI 70 GHz the upper curve displays also the case of 15 months of integration). At frequencies close to *WMAP* V band and LFI 70 GHz channel the polarised foreground is minimal. The figure shows 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, the CMB B mode and also over 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

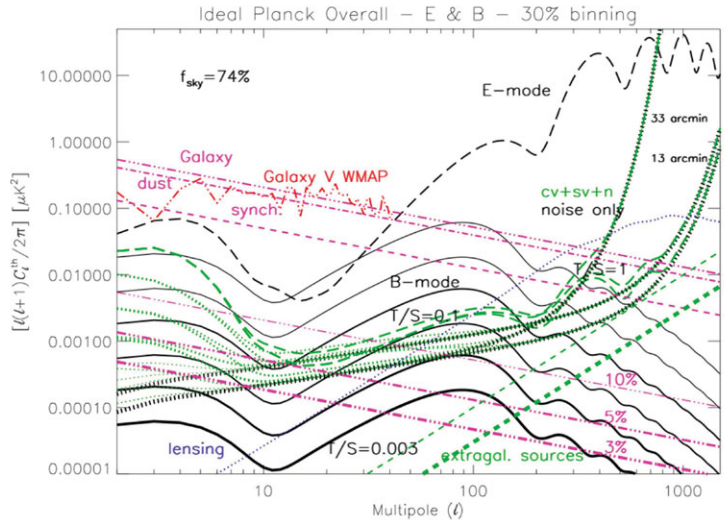

Figure 1. CMB E polarisation modes (black long dashes) compatible with *WMAP* data and CMB B polarisation modes (black solid lines) for different tensor-to-scalar ratios of primordial perturbations ($r \equiv T/S = 1, 0.3, 0.1, 0.03, 0.01, 0.003$, at increasing thickness) are compared to *Planck* overall 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 (Górski *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.

at the several % level, then the main limitation will come from instrumental noise. As shown in Fig. 1, values of $r > 0.05$ 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) by almost an order of magnitude. 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 (e.g. see Maris *et al.*, 2010) or systematic effects. *Planck* will also extend those investigations to polarization maps (see Mandolesi *et al.*, 2010; Tauber *et al.*, 2010 and references therein).

Planck will carry out an all-sky survey of the fluctuations in Galactic emission at its nine frequency bands. The HFI channels at $\nu \geqslant 100\,\mathrm{GHz}$ will provide the main improvement in the charcterization of the large-scale Galactic dust emission particularly in polarisation, while LFI will provide crucial information about the low frequency tail of this component. The LFI frequency channels, in particular at 30 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). Several interpretations of microwave (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; Lazarian & Finkbeiner, 2003). Another interesting component 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.*, 2003, Maris & Burigana, 2009, Maris *et al.*, 2006b).

The higher sensitivity, angular resolution, and frequency coverage of *Planck* will allow us to obtain very rich samples of extragalactic sources at mm and sub-mm wavelengths (Herranz *et al.*, 2009) and a 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)). Another 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 sources (Lin *et al.*, 2009).

3. 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.

References

Abdo, A. A., *et al.* 2009, *ApJ*, 700, 597
Ashdown, M. A. J., *et al.* 2007, *A&A*, 467, 761
Bartlett, J. G., *et al.* 2008, *Astronomische Nachrichten*, 329, 147
Bartolo, N., *et al.* 2004, *Phys. Rep.*, 402, 103
Bersanelli, M., *et al.* 2010, *A&A*, 520, A4
Boesgaard, A. M., *et al.* 1998, *ApJ*, 493, 206
Bonaldi, A., *et al.* 2007, *MNRAS*, 382, 1791
Burigana, C., *et al.* 1997, Int. Rep. TeSRE/CNR 198/1997, arXiv: astro-ph/9906360
Burigana, C., *et al.* 2001, *Experimental Astronomy*, 12, 87
Cho, J. & Lazarian, A., 2003, *New Astronomy Review*, 47, 1143
Collaudin, B., Passvogel, T. 1999, *Cryogenics*, 39, 157
Cremonese, G., *et al.* 2003, *New Astronomy*, 7, 483
Cumberbatch, D. T. *et al.* 2009, ArXiv e-prints 0902.0039
Dobler, G., *et al.* 2009, *ApJ*, 699, 1374
Draine, B. T. & Lazarian, A., 1998, *ApJL* 494, L19
Dupac, X., Tauber, J. 2005, *A&A*, 430, 363
Efstathiou, G. 2004, *MNRAS*, 349,603
Fermi/LAT Collaboration, 2009, *ApJ.*, 697, 1071
Górski, K. M. *et al.* 2005, *ApJ*, 622, 759
Hamimeche, S., Lewis, A. 2008, *Phys. Rev.* D77, 103013
Herranz, D. *et al.* 2009, *MNRAS*, 394, 510
Hildebrandt, S. R., *et al.* 2007, *MNRAS*, 382, 594
Hooper, D. *et al.* 2007, *Phys. Rev. D* 76, 083012
Hooper, D. *et al.* 2008, *Phys. Rev. D* 77, 043511
Janssen, M. A., Gulkis, S. 1992, in NATO ASIC Proc. 359: The Infrared and Submillimetre Sky after COBE, ed. M. Signore and C. Dupraz, 391
Jewell, J., *et al.* 2004, *ApJ*, 609, 1
Knox, L. 1995, *Phys. Rev. D* 52, 4307
Kogut, A., *et al.* 2009, arXiv:0901.0562
Lamarre, J. M., *et al.* 2010, *A&A*, 520, A9
La Porta, L., *et al.* 2008, *A&A*, 479, 641
Lazarian, A. & Finkbeiner, D., 2003, *New Astronomy Review*, 47, 1107
Leach, S. M., *et al.* 2008, *A&A*, 491. 597
Leahy, P., *et al.* 2010, *A&A*, 520, A8
Leach, S. M., *et al.* 2008, *A&A*, 491, 597
Lin, Y.-T., *et al.* 2009, *ApJ*, 694, 992
Lopez-Caniego, M., *et al.* 2006, *MNRAS*, 370, 2047
Maino, D., *et al.* 1999, *A&AS*, 140, 383
Mandolesi, N., *et al.* 1994, in Lecture Notes in Physics, Berlin Springer Verlag, Vol. 429, Present and Future of the Cosmic Microwave Background, ed. J. L. Sanz, *et al.*, 228
Mandolesi, N. *et al.* 2010, *A&A*, 520, A3
Maris, M., *et al.* 2006b, *A&A*, 452, 685
Maris, M. & Burigana, C., 2009, *Earth, Moon, and Planets*, 105, 2, 81
Maris, M., *et al.* 2010, arXiv:1010.0830
Rocha, G., *et al.* 2009, arXiv:1008.4948
Scott, D. & Smoot, G. 1998, *Phys. Lett. B*, 667, 246
Smoot, G. F., *et al.* 1992, *ApJ*, 396, L1
Tauber, J., *et al.* 1994, *ESA Journal*, 18, 239
Tauber, J., *et al.* 2010, *A&A*, 520, A1
The Planck Collaboration, 2006, astro-ph/0604069
Waelkens, A. *et al.* 2009, *A&A* 495, 697
Wandelt, B. D., *et al.* 2004, *Phys. Rev. D* 70, 083511
Wright, E. L., *et al.* 1996, *ApJ*, 458, L53