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Planck mission: challenges and expectations for cosmology and particle physics

C. Baccigalupi[1,2,3]

[1] SISSA/ISAS, Via Beirut 4, 34014 Trieste
[2] INFN, Sezione di Trieste, Via Valerio 2, 34127 Trieste
[3] Istituto Nazionale di Astrofisica – Osservatorio Astronomico di Trieste, Via Tiepolo 11, I-34143 Trieste, Italy, e-mail: bacci@sissa.it

Abstract. The Planck satellite of the European Space Agency, scheduled to be launched on May 14th, 2009, is designed to observe the microwave sky with unprecedented frequency coverage, sensitivity and angular resolution, in order to provide the most accurate measurement of the anisotropies in the Cosmic Microwave Background.
We review here the present status of the mission as well as the future milestones, give the main remarks on the forthcoming phase of data acquisition, analysis and interpretation, focusing on the leadership that Italian scientists and institutions represented for the entire Planck collaboration in the instrumental study, design, construction, and data analysis of one of the two instruments on board, the Low Frequency Instrument (Mandolesi et al. 2003). We describe the main scientific expectations and challenges for cosmology and particle physics, represented by this mission.

Key words. Cosmology: observations – Cosmology: theory

1. Introduction

The Cosmic Microwave Background (CMB) represents one of the pillars of modern cosmology. Together with the data concerning Big Bang Nucleosynthesis, Large Scale Structure, and Type Ia Supernovae, CMB total intensity and polarization anisotropies give evidence that the Universe is characterized by a Gaussian and scale invariant spectrum of primordial density perturbations, with a flat geometry described by the Friedmann-Robertson-Walker metric; it is made by about 4% of known baryons and leptons, 21% of still unknown dark matter, and 75% by a mysterious, negative pressure component known as dark energy, with an Hubble expansion flow corresponding to about 70 km/sec/Mpc and accelerating under the effect of the dark energy itself.

The CMB has been for decades at the center of an extraordinary observational and theoretical investigation, starting with the discovery of total intensity anisotropies by the COBE satellite (Smoot et al. 1992), continuing with the observations of many ground based and balloon-borne experiments (see http://lambda.gsfc.nasa.gov for a complete list of completed, operating and planned sub-orbital CMB experiments), culminating with the NASA WMAP satellite (Komatsu et al.

Send offprint requests to: C. Baccigalupi

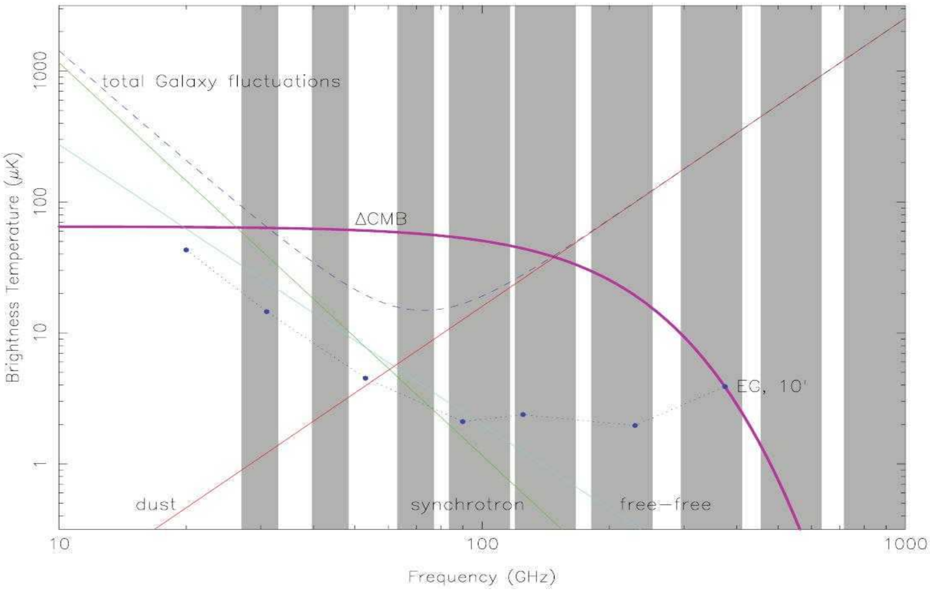

Fig. 1. A scheme of the Planck frequency coverage, taken from the Planck Blue Book available at www.sciops.esa.int/PLANCK. Grey stripes represent the Planck frequency bands. The thick, solid line represents the rms of CMB fluctuations in total intensity, while the frequency behavior of the most important diffuse foregrounds, namely dust, synchrotron and free free, are shown as thin, solid lines. Their superposition, corresponding to the dashed line, is also shown. The dotted dashed lines indicates the rms from unresolved extra-Galactic point sources.

2009), currently operating. These measurements gave access to the angular power spectrum of CMB anisotropies in total intensity (T) on all sky down to an angular scale of about 15 arcminutes. Anisotropies in T on smaller angular scales have been mapped, on limited portions of sky, by sub-orbital experiments (Reichardt et al. 2009). The CMB polarization anisotropies are potential tracers of most important information from the early Universe, and are commonly divided into E modes, dominated by scalar (density) fluctuations, and B, which is activated by vector or tensor modes (gravitational waves) in the primordial perturbations. The detection so far is limited to the E modes by sub-orbital experiments observing limited sky patches, as well as their correlation with T modes on all sky, down to about one degree (see Nolta et al. 2009, and references therein).

As we discuss below, these extraordinary results contributed significantly to the present picture of cosmology, but opened deep mysteries, some of which might have profound implications for fundamental physics. In addition, no tracer of the physics of the early Universe better than the CMB will be available for decades. For these reasons, after about 16 years of design and construction, the community is getting prepared for the analysis and interpretation of the Planck data, which are expected to push significantly ahead our knowledge of CMB anisotropies, impacting several fields in astrophysics, cosmology and particle physics; at the same time, several exploratory, sub-orbital observations are being carried out as pathfinders of a fourth CMB dedicate space probe.

2. The Planck satellite

Planck will observe the entire sky for a nominal duration of operations of 14 months, subject to extension, on 9 frequency channels

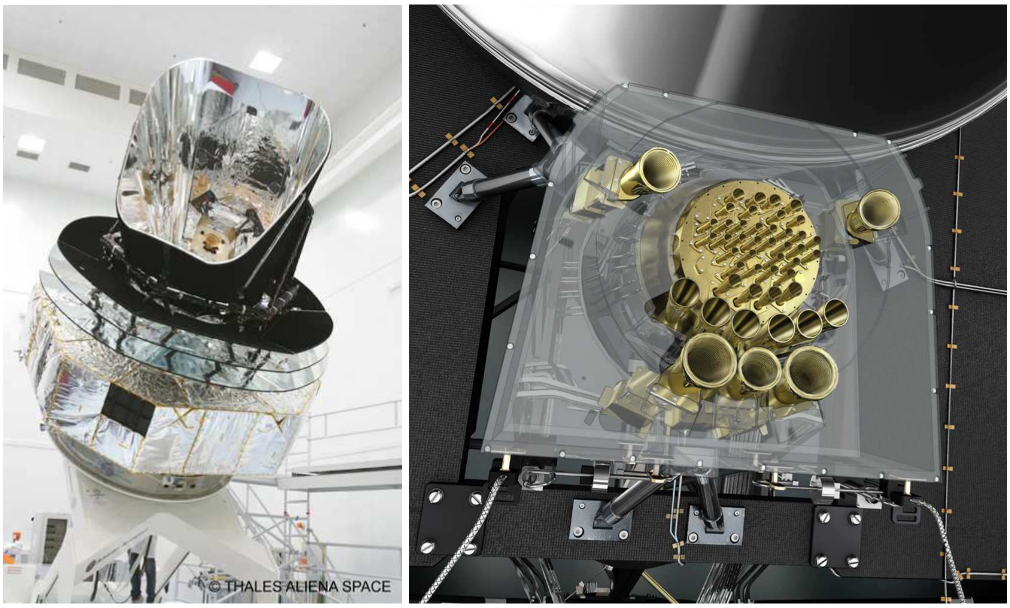

Fig. 2. Right: a recent snapshot of the Planck satellite. Left: focus on the focal plane. The pictures are taken from the Planck web page at www.sciops.esa.int/PLANCK.

ranging from 30 to 857 GHz, roughly ten times larger than the WMAP frequency coverage. The latter is needed in order to control the contamination of different kinds of foregrounds, which may be efficiently subtracted if known on a sufficiently large frequency interval. Figure 1 well represents the Planck frequency setup, and the need of monitoring Galactic and extra-Galactic emission on a large frequency interval. The Planck angular resolution corresponds to 5 arcminutes in the high frequency channels, down to 217 GHz, gradually decreasing at lower frequencies, reaching 33 arcminutes in the lowest one. The instrumental sensitivity is conceived in order to be able to measure the angular power spectrum down to the arcminute scale in total intensity, ten arcminute scale for polarization.

The Planck primary mirror, about 1.5 m, reflects the light into the secondary one and then in the focal plane, made by the radiometers of the Low Frequency Instrument (LFI, Mandolesi et al. 2003), cooled at about 20 K and operating between 30 and 70 GHz, and the bolometers of the High Frequency Instrument (HFI, Lamarre et al. 2003) operating from 100 to 857 GHz, and cooled at about 0.1 K. The observation region is L2, the Lagrangian point in the Earth-Sun system, situated beyond the Moon, at about 1.5 million km from Earth. In figure 2, the Planck spacecraft and the focal plane are represented.

The role of Italian scientists and institutions has been central since the initial conception of a post COBE and almost definitive CMB mission, in 1993, and has been made possible by the continuous support of several funding resources, in particular the Italian Space Agency. The construction of the LFI instrument on board Planck has been leaded by personnel of the IASF, in Bologna, and the physics department in Milan; with the help of scientists from many Italian institutions in Rome, Padua, Catania, Bologna, Milan, together with several other institutions in Europe and US which we do not have space for listing here, the Italian community is preparing to undertake the challenge of data analysis, with one of the two Data Processing Centers (DPC) located in Trieste, as we'll discuss below.

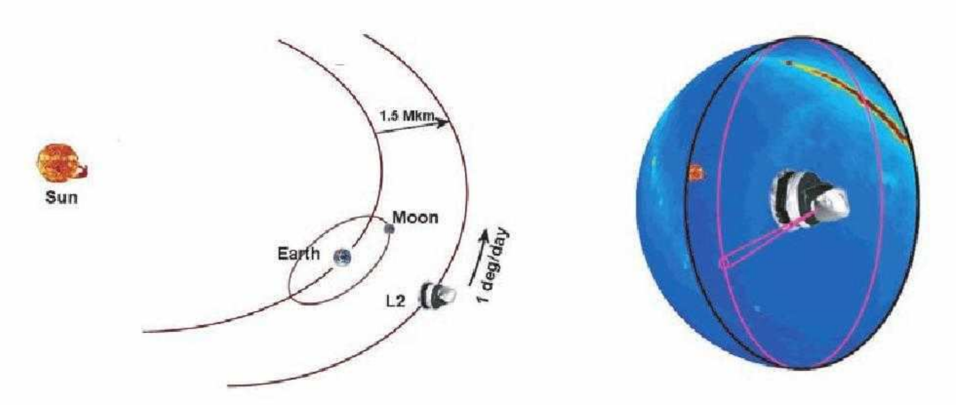

Fig. 3. A sketch of the Planck observation location with respect to Sun, Earth and Moon, showing the main features of the scanning strategy, from the Planck Blue Book, available at www.sciops.esa.int/PLANCK.

3. Data analysis

For a nominal mission duration of 14 months, subject to extension, the satellite makes one complete spin every minute and adjusts the observation plane by two arcminutes in between each spin, covering one degree per day in its motion within L2. Each detectors records the sky radiation tens of times per second, comparing it with a fixed reference on board. A scheme of the scanning strategy, also indicating the observation location in the solar system, is shown in figure 3. The row data are collected by the Mission Operation Center located in Darmstadt, Germany, and sent to the two DPCs, located in Trieste (operated jointly by the Astronomical Observatory, www.ts.astro.it and SISSA, www.sissa.it), and Paris (operated jointly by the IAP, www.iap.fr, and IoA in Cambridge, www.ast.cam.ac.uk) for the analysis, which is divided in levels. Level 1 starts from the row time ordered data (TOD) series coming from each detectors, and proceeds up to the calibration in physical units. Level 2 compresses the calibrated TODs in sky maps, at the nine frequency channels of Planck. In the level 3, the multi-frequency maps are used to extract the CMB signal, its angular power spectrum and cosmological parameters, the main Galactic and extra-Galactic astrophysical emissions. Up to level 2, the analysis proceeds independently in the two DPCs, while the data are shared in level 3. After 14 months of observations, starting at the end of August, 2009, the data are analyzed exclusively within the Planck collaboration, for two more years (proprietary period), and successively released, in terms of scientific papers and actual archive data.

4. Challenges and scientific expectations

The CMB is the best tracer of physics in the early universe and large scale cosmology that we'll have for decades. At the present, we have solid measurements of the power spectrum of anisotropies in the total intensity, and a limited knowledge of the polarization one. Despite of the many efforts and serious works in the literature, little is known about the reliability of the cosmological information which may be obtained from higher order statistics in the present data. Although the measurements contributed substantially to the cosmological picture we have today, the community is preparing to access the unknown CMB signal, starting with Planck and the operating and planned sub-orbital probes.

For angular resolution, sensitivity, frequency and sky coverage, Planck will have a major impact in all the areas of science which are connected to the study of the CMB. A glimpse of the improvement that we expect for CMB anisotropies from Planck is repre-

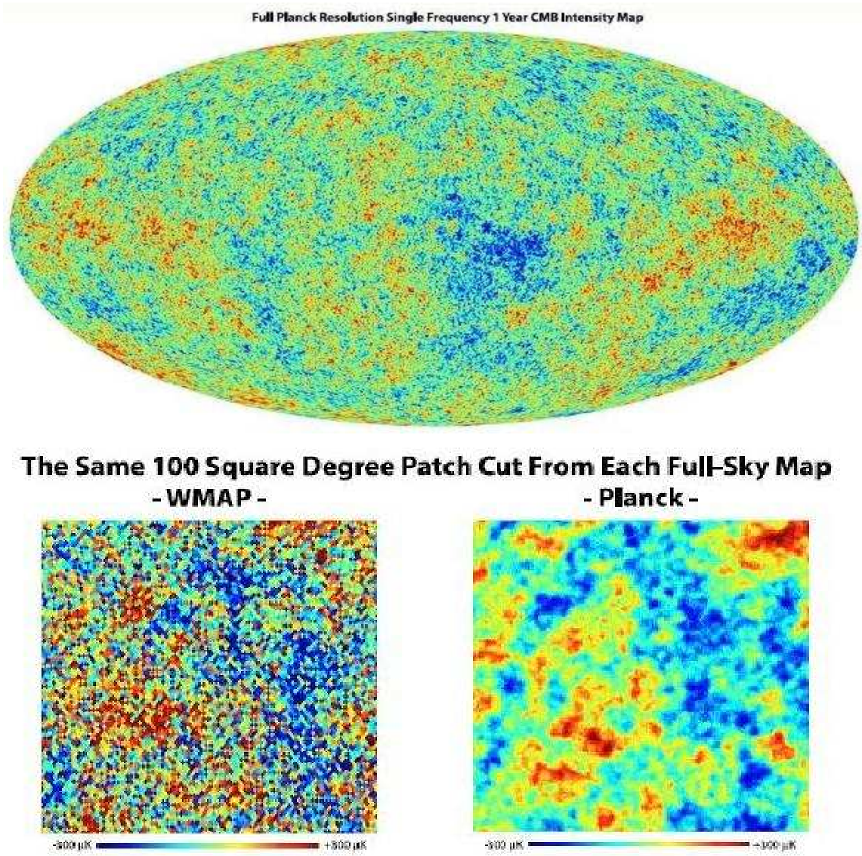

Fig. 4. Upper panel: a simulation of the CMB all sky total intensity anisotropies which Planck is able to obtain; the map has been obtained using super-computing facilities at NERSC, Berkeley, California, and the signal is represented using the HEALPix software Gorski et al. (2005). Bottom panels: a focus on few degrees wide region, comparing the WMAP performance against Planck, showing how the CMB pattern is expected to be mapped accurately by the latter, up to the smallest significant angular scales.

sented in figure 4. Together with the tightening, by a factor of about 10, of all the known cosmological parameters related to the early universe, cosmological geometry and content, several CMB observables are currently unknown or poorly constrained, and Planck is forecasted to have a major role in the progress of the knowledge of those. We briefly discuss some of them here. Due to well known geometrical features, and effects on the growth of scalar perturbations, the CMB is known to be sensitive to the sum of neutrino masses, and Planck is expected to increase the limit from the current 0.5 eV to about 0.06 eV (Gratton et al. 2008). The CMB anisotropies coming from last scattering undergo several processes which are still undetected but within the reach of Planck sensitivity, like gravitational lensing, possibly containing information on the cosmological expansion at the epoch in which dark energy started to dominate the expansion (Acquaviva and Baccigalupi 2006). Or processes which are at the present poorly known, particularly in polarization, like the measure of the power from reionization, which is expected to benefit greatly from the control of foreground emission which is achievable thanks to the huge frequency coverage of

Planck (Popa et al. 2007). The latter aspect is closely related to one of the most ambitious tasks of CMB observation nowadays, i.e. the detection of B modes in the polarization; indeed, they are sourced by primordial gravitational waves, and amplified by reionization on large scales; again, due in particular to the control of the diffuse Galactic foregrounds achievable thanks to the frequency coverage, Planck will allow to investigate as never before the existence of this component (Efstathiou et al. 2009); that might have most important implications for the physics of the early universe, as well as, in case of positive detection, open up the direct search for these gravitational waves in the far future; as already mentioned, this is possibly a line of research for theoretical and observational CMB which will extend beyond Planck; a series of sub-orbital experiments (see lambda.gsfc.nasa.gov) are pathfinders for a post-Planck space mission, dedicated to the polarization measurements leaded by ESA (De Bernardis et al. 2008) and NASA (Dodelson et al. 2009). The possible departure from Gaussianity in the CMB anisotropies, of primordial origin, is currently debated and uncertain with the available data (Yadav and Wandelt 2008); Planck is expected to have a sensitivity to primordial non-Gaussianity about 10 times better than previous probes, and the this debate, and the relative is one of the major expectations from Planck concerning the early universe. Due to the huge interval of scales and cosmological epochs that the CMB probe, Planck is forecasted to extend significantly the present constraints on the Jordan Brans Dicke modification of gravity on cosmological scales (Acquaviva et al. 2005). Planck will investigate important and yet not understood aspects of the present data, like the well known the north-south asymmetry (Hoftuft et al. 2009); it will possibly discriminate among different causes of such unexpected feature, at odds with the isotropy and homogeneity principle which is the basis of modern cosmology, being able to identify or exclude a solar system or Galactic origin for that. Concerning astrophysics, which we do not have space here to address properly, we just mention that Planck is expected to discover tens of thousands new Galaxies, a thousands of galaxy clusters, as well as a detailed mapping of the diffuse Galactic gas in our own Galaxy in its previously unexplored frequency range, with the imaginable consequences for astrophysics, galaxy formation, etc.

In conclusion, Planck certainly represents one of the major scientific challenges for modern physics, and in particular a challenge and opportunity for the community of Italian scientists, which were able to lead the design, construction and data analysis of one of the instruments on board Planck.

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References

Acquaviva, V. and Baccigalupi, C. 2006, Phys. Rev. D, 74, 103510

Acquaviva, V. et al. 2005, Phys. Rev. D, 71, 104025

De Bernardis, P. et al. xxx.lanl.gov/abs/0808.1881

Dodelson, S. et al., xxx.lanl.gov/abs/0902.3796

Efstathiou, G., Gratton, S., Paci, F. 2009, MNRAS, 397, 1355

Gorski, K. M., et al. 2005, ApJ, 622, 759

Gratton, S., Lewis, A., Efstathiou, G. 2008, Phys. Rev. D, 77, 083507

Hoftuft, J. et al. 2009, ApJ, 699, 985

Komatsu, E. et al. 2009, ApJS, 180, 330

Lamarre, J. M. et al. 2003, xxx.lanl.gov/abs/astro-ph/0308075

Mandolesi, N. et al. 2004, xxx.lanl.gov/abs/astro-ph/0411412

Nolta, M. R. et al. 2009, ApJS, 180, 296

Popa, L. et al. 2007, New Astron. Rev., 51, 298

Nolta, E. et al. 2009, ApJ, 694, 1200

Smoot, G. F.. et al. 1992, ApJ, 396, L1

Yadav, A., Wandelt B. J. 2008, Phys. Rev. Lett., 100, 181301