PROCEEDINGS OF SCIENCE

Looking at the Universe with *Planck*

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on behalf of the *Planck* collaboration[†]

Planck was successfully launched on May 14th, 2009, from the Kourou space port, in French Guyana. I first recall the objectives that we set out to fulfill fourteen years ago at the time of the down-selection by ESA. I then mention technological breakthroughs which needed to be made, provide an overview of some of the main steps of the project till now, and report on the exciting scientific outlook in light of the knowledge we now have of the actual performances of the two on-board instruments. Indeed, by early June 2010, *Planck* had just completed gathering data on the entire sky at least once by all detectors, and a first rendering of the full sky was presented at the conference. This and other evidence convince us that *Planck* is very likely to exceed expectations. Stay tuned!

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[*] Speaker.
[†] Our pre-launch mission paper, now published, has 500 authors.

The measurement goals of *Planck* may be stated rather simply: to build an experiment able to perform the "ultimate" measurement of the primary CMB temperature anisotropies, which are a fantastic source of information for cosmology and fundamental physics (see below). This requires:

- full sky coverage and a good enough angular resolution in order to mine all scales at which the Cosmic Microwave background (CMB) primary anisotropies contain information ($\gtrsim 5$ minutes of arc, since at smaller scales seconday fluctuations dominate)

- a very large frequency coverage, from 30 GHz to 1 THz, to remove precisely the astrophysical foregrounds, with a sensitivity at each of the 9 survey frequencies in line with the role of each map in determining the CMB properties.

For the measurement of the polarisation of the CMB anisotropies, *Planck* goal was "only" to get the best polarisation performances with the technology available at the design time. In the course of time, and with the successful developments of enabling technologies, we boosted our initial polarisation goals and set out to reach the ambitious sensitivity levels described below (last line of Table 1).

This is on these simple but ambitious goals (and on the proposed way of reaching them) that, after 3 years of preparatory work, the project was selected by the European Space Agency (ESA), as the 3^{rd} Medium size mission of its Horizon 2000+ program. This selection occurred in march 1996, *i.e.,* contemporaneously with that of *WMAP* by NASA, which rather proposed reaching earlier less ambitious goals wich could be reached with only incremental development on existing technology. Table 1 summarises the main performance goals of *Planck*, both in angular resolution and sensitivity expressed as the average detector noise within a square patch of 1 degree of linear size, c_{noise}, for the 14 months baseline duration of the mission. This duration allows covering twice all the sky by nearly all the detectors. It is interesting to note that if we take the noise performance figure for the average of the central CMB frequencies (the 100-143-217 GHz HFI channels, assuming all the other channels are devoted to foregrounds removal), one finds a goal sensitivity of 0.5 μK.deg in temperature and 1 μK.deg for the Q & U Stokes parameters.

	LFI goals			HFI goals					
ν [GHz]	30	44	70	100	143	217	353	545	857
FWHM [arcmin]	33	24	14	9.5	7.1	5.0	5.0	5.0	5.0
c^{T}_{noise} [μK.deg]	3.0	3.0	3.0	1.1	0.7	1.1	3.3	33	1520
$c^{Q\ or\ U}_{noise}$ [μK.deg]	4.3	4.3	4.3	1.8	1.4	2.2	6.8		

Table 1: Summary of *Planck* performance *goals* for the required 14 months of routine operations, which allows nearly all detectors to map the entire sky twice. *Requirements* on sensitivity were simply two times worse than the stated goals. Central band frequencies, ν, are in Gigahertz, the FWHM angular sizes are in arc minute, and the (sky-averaged) sensitivities c^{X}_{noise}, with $X = T, Q$ or U, are expressed in μKdeg; this number indicates the rms detector noise, expressed as a equivalent temperature fluctuation in μK, which is expected once it is averaged in a pixel of 1 degree of linear size (*e.g.,* multiply by 12 to get the rms of the noise in 5 arcminute pixels).

WMAP (in flight)					
ν [GHz]	23	33	41	61	94
FWHM [arc min]	49.2	37.2	29.4	19.8	12.6
c^T_{noise} [μK.deg]	12.6	12.9	13.3	15.6	15.0

Table 2: Summary of *WMAP* in-flight performance per full year of operations. Same units than in Table 1.

Actually, we now know that the mission duration is very likely to extend to 30 months of survey operation, allowing to improve the aggregate sensitivity above to about $1/3\,\mu$K.deg in temperature. The magnitude of this step forward, if achieved, may be judged by comparing with the *WMAP* sensitivity which is given in Table 2. Indeed, the aggregate sensitivity of the *WMAP* 60 & 90 GHz channels is $\sim 10.8\,\mu$K.deg in a year, which would imply about $(10.8*3)^2 \sim 1000$ years of *WMAP* operations needed to reach the expected *Planck* sensitivity! This, combined with higher angular resolution by a factor larger than 2 of *Planck*-HFI, will allow to map at least 10 times more temperature modes (multipoles) than *WMAP*. As a result, we shall really start exploring the physics of the mechanism, inflation or other, which initiated the formation of structures, with less reliance on theoretical priors than it is currently possible.

In order to achieve the ambitious sensitivity goals of *Planck*, we proposed for HFI to use a small number of detectors, limited principally by the photon noise of the background (for the CMB ones), in each frequency band. This implied to achieve several technological feats never achieved in space before:

- sensitive & fast bolometers with a Noise Equivalent Power $< 2\times10^{-17}\,\mathrm{W/Hz^{1/2}}$ and time constants typically smaller than about 5 milliseconds (which thus requires to cool them down to ≈ 100 mK, and to build them with a very low heat capacity & charged particles sensitivity)
- total power read out electronics with very low noise, $< 6\,\mathrm{nV/Hz^{1/2}}$ in a large range, from 10 mHz (1 rpm) to 100 Hz (*i.e.,* from the largest to the smallest angular scales to measure at the *Planck* scanning speed)
- excellent temperature stability, from 10 mHz to 100 z, such that the induced variation be a small fraction of the detector temporal noise (cf.[2] for details):
  - better than $10\,\mu\mathrm{K/Hz^{1/2}}$ for the 4K box (assuming 30% emissivity)
  - better than $30\,\mu\mathrm{K/Hz^{1/2}}$ on the 1.6K filter plate (assuming a 20% emissivity)
  - better than $20\,\mathrm{nK/Hz^{1/2}}$ for the detector plate (a damping factor ~ 5000 needed)

The LFI required very low noise HEMT amplifiers (therefore cooled to 20 K) and very stable cold reference loads, at 4 K. In addition, *Planck* requires:

- a low emissivity telescope with very low side lobes (*i.e.,* strongly under-illuminated)
- no windows, and minimum warm surfaces between the detectors and the telescope
- a quite complex cryogenic cooling chain (cf. figure 1) which begins by reaching ~ 40 K via passive cooling, by radiating about 2 Watts to space, followed by three active stages, at about 20 K, 4 K, and 0.1 K:

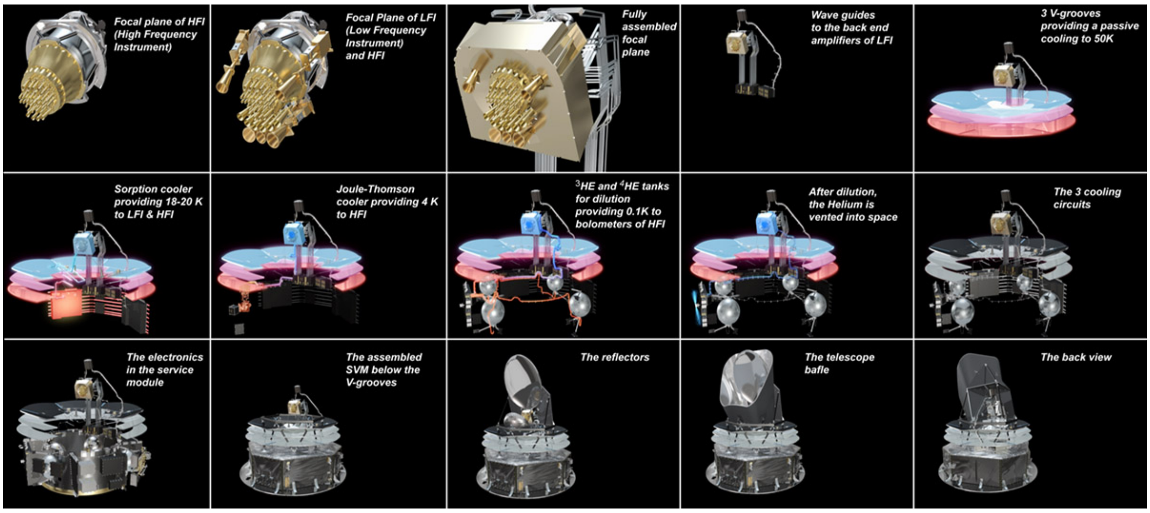

Figure 1: *Planck* build-up from the inside out. Going from left to right, one sees on the top row (t1) the HFI instrument with its 52 detector horns poking out of it's outer shell at 4 K. (t2) HFI is surrounded by the 11 larger horns from the LFI. HFI and LFI together form (t3) the focal plane assembly from which (t4) the electrical signal departs (though a bunch of wave guides for the LFI and a harness of wires for HFI) to connect to the warm electronics parts of the detection chain which are located within the service module at ~ 300 K. (t5) The (top) cold and warm (bottom) parts are separated by three thermally isolating V-grooves which allow radiating to space heat from the spacecraft sideways and quite efficiently. The third (top) V-grooves operating temperature is about 40 K.

On the middle row, one sees (m1) the beds of the sorption cooler and it's piping around the V-groove, bringing the overall focal-plane structure to LFI's operational temperature of ~ 18 K. (m2) The back-to-back (to damp the first harmonics of the vibrations) compressors of the 4 K cooler allow bringing HFI outer shell to 4 K, while (m3) isotopes from the He^3 tank and the three He^4 tanks are brought to the mixing pipes within HFI to cool filters (within the horns) to 1.6 K and the bolometer plate to 0.1 K, before (m4) being released to space. (m5) The passive cooling and the three active stage constitute this complex but powerful cooling chain in space.

On the bottom row, one can also see (b1) some of the electronic boxes in the service module (SVM) which in addition to the warm part of the electronic and cooling chains also contain all "services" needed for transmitting data, reconstructing the spacecraft attitude, powering the whole satellite... The bottom of the SVM is covered with solar panels, while supporting struts begin on its top which allows (b3) positioning the secondary and primary reflectors. The top part is surrounded by a large baffle to shield at best the focal plane from stray-light. The back view (b5) allows distinguishing in the back the supporting structure of the primary mirror, and the wave guides from LFI. The spin axis of *Planck* (vertical on these plots) is meant to be close to the sun-earth line, with the solar panel near perpendicular to that line and the rotation of the line-of-sight (at 1 rpm) causing the detectors to survey circles on the sky with an opening angle around 85 degrees. Copyright ESA.

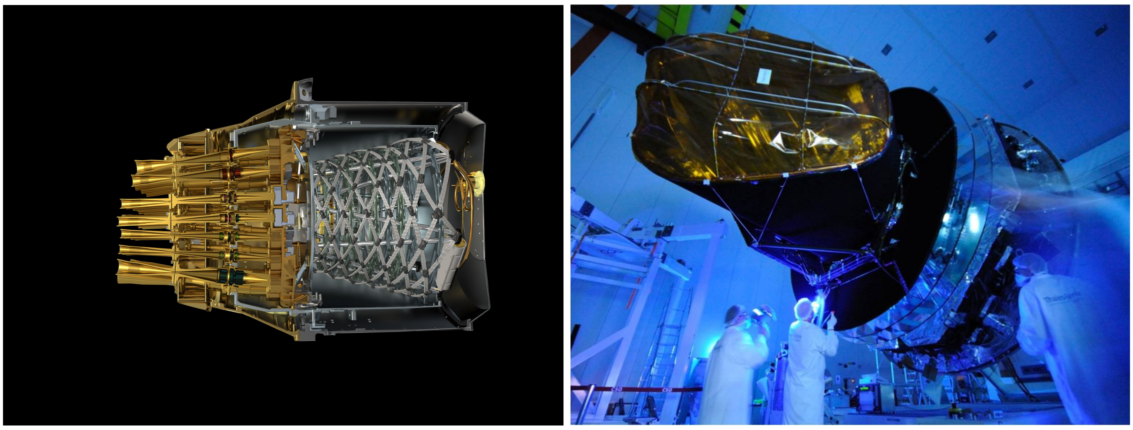

Figure 2: The cut-out at left displays the russian doll arrangement of the HFI. Starting from the left, one sees the back-to-back horns going through HFI outer shell at 4 K, the filters fixed on the 1.6 K inner shell and shown in different colors according to their central frequency, followed by the horn on the top of the bolometers encasing at 0.1 K. These encasings are fixed on a plate at the end of the "basket weaving" of the electrical wires and of the dilution piping. It is within these pipes that the mixing of the He^3 and He^4 takes place and lowers the temperature from the 1.6K shell at the right end to the 0.1 K of the bolometer plate at the other end. The picture of *Planck* at right was taken in Kourou when it was time to "dust if off" as part of the preparations for launch.

- 20 K for the LFI, with a large cooling power, ∼ 0.7 Watts, provided by H_2 Joule-Thomson sorption pumps developed by JPL, USA.
- 4 K, 1.6 K and 100 mK for the HFI (the 15 milli-Watts cooling power at 4 K is provided by mechanical pumps provided by the RAL, UK, in order to perform a Joule-Thomson expansion of He; the 1.6 K stage has a pre-cooling power of about 0.5 milli-Watts, thanks to another Joule-Thomson expansion, while the final dilution fridge of He^3 & He^4, from a French collaboration between Air Liquide and the CRTBT, can lift 0.2 micro-Watts at 0.1 K.
- a thermal architecture optimised to damp thermal fluctuations (active+passive)

Furthermore, a tight control of vibrations is needed, in particular since the dilution cooler does not tolerate micro-vibrations at sub-mg level. And as little as 7×10^{10} He atoms accumulated on the dilution heat exchanger (an He pressure typically at the 1×10^{-10} mb level) would be too much. Fig. 2-a shows how HFI was designed to reach these objectives.

These top-level design goals have now been turned into real instruments, which went through several qualification models. Before delivering the actual flight model of both instruments to industry for integration with the satellite, both instrumental consortia organised extensive calibrations campaigns, starting at the individual components levels, then at the sub-systems levels (*e.g.,* individual photometric pixels), then at instrument level. For HFI, the detector-level tests were done mainly at JPL in the USA, and the pixel level tests were performed in Cardiff in the UK, while the instrument calibration was performed at the Institut d'Astrophysique Spatiale in Orsay, France from April till the end of July 2006. During that period, we obtained in particular 19 days of scientific data at normal operating conditions. We could then confirm that HFI satisfies all our

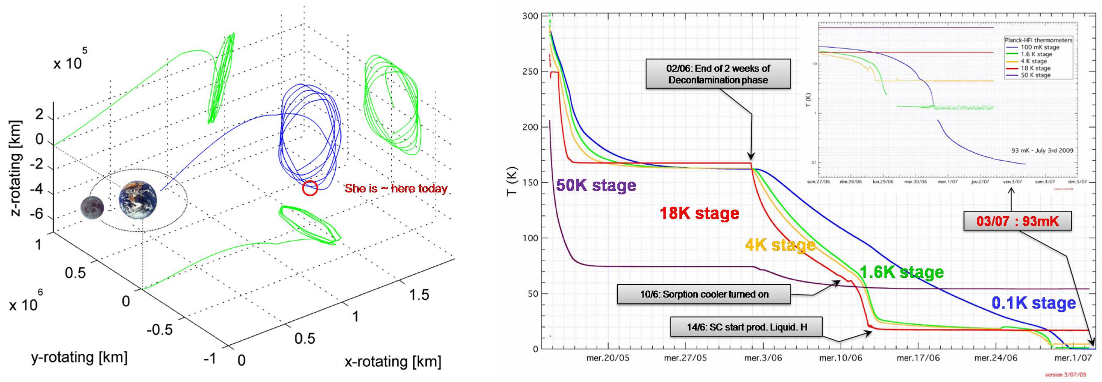

Figure 3: a) Spacecraft trajectory to and on the L2 orbit. b) Cooling sequence of *Planck*, showing the various stages reaching in turn their operational temperature, till the dilution plate actually reached 93 mK on July 3rd. Credit ESA and HFI consortium.

requirements, and for the most part actually reaches or exceeds the more ambitious design *goals*, in particular concerning the sensitivity, and speed of the bolometers, the very low noise of the read out electronics and the overall thermal stability. In addition, the total optical efficiency has been verified to be satisfactory, optical cross-talk to be negligible, as well as the current cross-talk is weak. Main beams are well-defined and are quite well described by the models, polarisation measurements confirm expectations, etc. The LFI instrument also went through detailed testing around the same time and it reaches many of its ambitious requirements.

The integration of the LFI and HFI instruments was performed at Thales premises in Cannes in November 2006 and within a year, by December 2007, the full satellite was ready for vibration testing. *Planck* was then flown from Cannes to ESA's ESTEC centre (in Noordwijk, Holland) where among other things it went through load balancing on April 7th, before travelling again to the "Centre Spatial de Lièges" (CSL) in april 2008. This ultimate system-level (ground) test, with all elements of the cryogenic chain present and operating, demonstrated in particular the following: a) the dilution system can work with the minimal Helium 3 and 4 flux, which should allow 30 months of survey duration (nominal duration being 14 months!). b) the extremely demanding temperature stability required (at 1/5 of the detection noise) has been verified, c) bolometers sensitivities in flight conditions are indeed centered around their goal.

Planck was then shipped to Kourou, prepared for launch (see fig. 2-b), and after a few more nerve-wracking delays, we finally lost sight of *Planck* for ever (when it was covered by the SYLDA support system on the top of which laid *Herschel* for a joint launch). Launch was on May 14th, and it was essentially perfect. After separating from *Herschel*, *Planck* was set in rotation and started its travel to the L2 Lagrange point of the sun-earth system. L2 is at 1.5 million kilometres away from earth, *i.e.,* about 1% further away from the sun than the earth. The final injection in the L2 orbit was at the end of June (see figure 3-a), at the same time than the cooling sequence ended successfully. Indeed, figure 3-b shows how the various thermal stages reached their operating temperature, cooling of corse from the outside-in, and closely following the predicted pattern.

Once at L2, a calibration and performance verification phase was conducted till mid-august, to insure that all system are working properly and that instrumental parameters are all set at best.

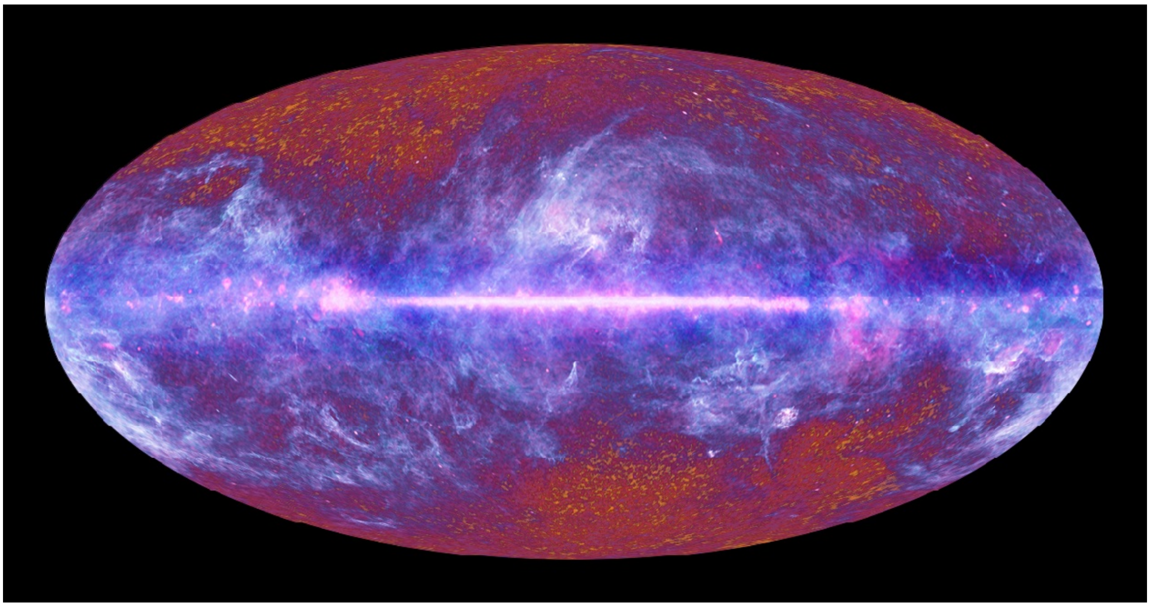

Figure 4: This all-sky image has been obtained by combining data spanning the full frequency range of *Planck*, probing different physical processes, both local and cosmological; it thus represents a synthesis of the wide range of information that *Planck* is able to provide. Although it shows the combined features of many sources of emission, individual frequency maps are much more clearly dominated by the emission of one or a few sources, facilitating their separation. For example, even though in this image the CMB shows through clearly only in limited regions (as a reddish fluctuating background), the central frequencies of *Planck* are actually dominated by the CMB itself over much larger areas. While the combination of maps to create that image was designed to illustrate the structure of the foreground emission, similar techniques may be used instead to isolate the primordial background component for cosmological analyses. Copyright ESA, HFI and LFI consortia.

From August 13th to 27th, we conducted a “First Light Survey” in normal operational mode for an ultimate verification of the parameters and of the long-term stability of the experiment. We found the data quality to be excellent, and the Data processing Centre pipelines were successfully operated as hoped. Indeed the first maps were produced within days of getting the data, and clearly showed consistency of the mapping of the CMB component by the two instruments. Such speed is by no means the standard in CMB mapping when fluctuations have an rms $\sim 100\,\mu$K. Since then, the operations have been extremely smooth, and the instrumental teams have further improved the data processing, in particular to deal with the main in-flight surprise, the abundance of cosmic ray hits. These hits create showers of secondaries which induce many “glitches" in the data flow of some bolometers and also relatively slow temperature fluctuations of the bolometer plate which create an additional noise correlated among all detectors.

Figure 4 displays a composite image, made out of our 9 emission maps, which we released at the time of the conference. It was designed to make the Galactic contributions clearly stand out as a haze in front of the afterglow of the Big Bang which appears in reddish tones at high Galactic latitudes. This vividly illustrates the need to collect data on all foregrounds emissions, including the extragalactic ones due mostly to compact sources and clusters of galaxies. It is only when all contributing foregrounds are well understood that one can be confident that residuals from their cleaning does not affect the CMB properties. This is an area of active work of the *Planck* collaboration and first results of our investigations on foreground emissions will be presented in January 2011 at a topical conference that we are organising in Paris. This is the first time that the frequencies where the dust emission dominates, say at $\nu > 217\,\mathrm{GHz}$, are mapped over the full sky, and that is surely needed to insure that this emission is removed with the exacting accurary level required by *Planck* scientific goals.

We shall deliver to ESA in December 2010, as planned, an “Early Release Point Source Catalogue” based on a rapid analysis of this first coverage of the sky. Its release to the community by ESA on January 11th 2011, during the conference, will allow astrophysicists to propose follow-ups by *Herschel* during its expected cryogenic life. A second data release based on the data from the nominal 14 months mission is slated for delivery in december 2012. That release should include the nine full sky maps at the six frequencies covered by HFI and the three ones by LFI, possibly supplemented by polarisation maps, as well as maps of identified astrophysical components (CMB, Galactic emissions, extragalactic sources catalogue), some ancillary information (*e.g.,* on beams, spectral transmission, etc), accompanied by about 50 scientific papers describing the mission, how the “products” were obtained, validated, and the results of a first pass of scientific exploitation by the Planck collaboration itself, encompassing in particular the implications of the measured statistical properties of the CMB.

Since our anticipation from the measured Helium consumption in flight is that the mission duration will substancially exceed the nominal duration of 14 months (to probably reach 30 months), we plan a further release, about a year later on the basis of the extra data which might allow covering as much as five times in total the sky. In addition to an improved sensitivity, this extra duration will foremost allow greater data redundancy and therefore a tighter control of all systematic effect which can be searched for with a longer baseline. This should allow us detecting the gravitational wave stochastic background predicted in one interesting class of inflationary models, providing the long thought after “smoking gun” of inflation, or otherwise put meaningful constraints on the viable inflation models remaining.

In conclusion, Planck is now in normal operation and performances are as expected or better. This gives us confidence that the scientific program of *Planck* can be carried through as anticipated. The dataset shall allow addressing many key cosmological questions, including the existence of a primordial gravitational wave background, or that of highly revealing deviations from the current minimal model, where the primordial fluctuation can be purely Gaussian, adiabatic, scale-free, in a strictly flat spatial geometry with a dark energy component indistinguishable from a pure cosmological constant, and (cosmologically) negligible neutrinos masses.

A rather complete overview of the scientific Program of *Planck* can be found in the so-called “Blue Book” which was issued in 2004. It can be downloaded from

http://www.planck.fr/IMG/pdf/Planck_book.pdf.

In addition, we submitted a series of pre-launch papers (all with a title starting with “Planck pre-launch status”. giving many details of the design and tests of the mission ([4]), the instruments, and some of their components ([1] and [3]).

Acknowledgments

Planck is the result of the efforts of a large industrial and research team, which includes a large fraction of Europe's far infrared, submillimeter and CMB community, as well as a large number of CMB researchers from the US. *Planck* (http://www.rssd.esa.int/Planck) is a project of the European Space Agency with instruments funded by ESA member states (in particular the lead countries: France and Italy) with special contributions from NASA (USA) and with the telescope reflectors provided by a collaboration between ESA and a scientific consortium led and funded by Denmark. The project involves about 50 participating scientific institutes. The Planck Science team comprises Marco Bersanelli, François R. Bouchet, Georges Efstathiou, Jean-Michel Lamarre, Charles Lawrence, Nazzareno Mandolesi, Hans-Ulrick Norgaard-Nielsen, Jean-Loup Puget, Jan Tauber, Andrea Zacchei. The LFI consortium is led by Reno Mandolesi. The HFI consortium is led by Jean-Loup Puget and François R. Bouchet.

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