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The Planck mission

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Abstract

We present an overview of the European Space Agency's Planck mission, its scientific objectives and the main elements of its technical design. The current programmatic status of Planck within ESA's Scientific Programme, implementation plans, and near-term milestones are also outlined.

Keywords: European Space Agency; Planck mission; Cosmic Microwave Background

1. Science

Planck (http://astro.estec.esa.nl/Planck) is a space observatory designed to image the temperature anisotropies of the Cosmic Microwave Background (CMB) over the whole sky, with unprecedented sensitivity ($\Delta T/T \sim 2 \times 10^{-6}$) and angular resolution (better than 10 arcmin). Planck will provide a major source of information relevant to several cosmological and astrophysical issues, such as testing theories of the early universe and the origin of cosmic structure.

The ability to measure to high accuracy the angular power spectrum of the CMB fluctuations will allow the determination of fundamental cosmological parameters such as the density parameter (Ω_0), and the Hubble constant H_0, with an uncertainty of order a few percent (e.g., Bersanelli et al., 1996, Bond et al., 1997; Efstathiou and Bond, 1999), Planck will not only measure the temperature fluctuations of the CMB, but also its polarization state. This measurement (e.g., Seljak, 1997) will not only yield new scientific results, but will also help to analyze the CMB temperature anisotropies (in particular by resolving degeneracies in the estimation of some cosmological parameters; see Zaldarriaga et al., 1997; Kamionkowski and Kosowsky, 1998).

In addition to the main cosmological goals of the mission, the Planck sky survey will be used to study in detail the very sources of emission which "contaminate" the signal due to the CMB, and will result in a wealth of information on the properties of extragalactic sources, and on the dust and gas in our own galaxy (e.g., de Zotti et al., 1999). One specific notable result will be the measurement of the Sunyaev-Zeldovich (SZ) effect in many thousands of galaxy clusters (Aghanim et al., 1997; Pointecouteau et al., 1998).

2. Payload

The scientific prescription which will allow Planck to meet its ambitious objectives calls for:

- an offset telescope with a physical aperture of size ~1.5 m to achieve the angular resolution.
- state-of-the-art broadband detectors covering the range ~25–1000 GHz, to achieve the required sensitivity and the ability to remove foreground sources of emission.
- a survey with all-sky coverage carried out from a far-Earth orbit.
- extreme attention to rejection of unwanted systematic effects.

To achieve this prescription a payload was conceived for Planck (Bersanelli et al., 1996) consisting of three basic components: (1) a telescope and baffling system,

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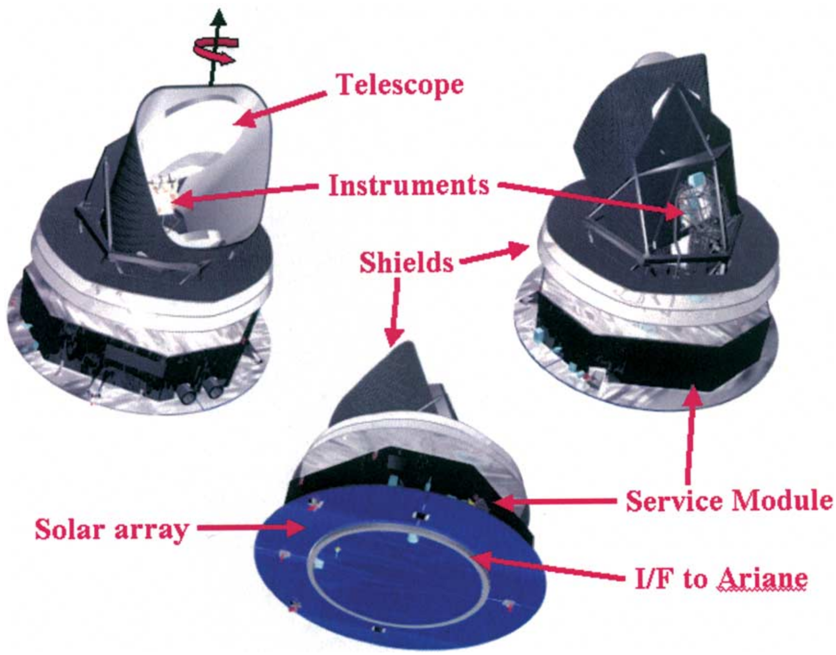

Fig. 1. A conceptual view of the arrangement of the main elements of the Planck payload. The instrument focal plane unit contains both low and high frequency detectors. The function of the large shield surrounding the telescope is to control the far sidelobe level of the radiation pattern as seen from the detectors. Specular cones thermally decouple the Service Module (located below the payload) from the Payload Module, and allow the payload environment to reach its nominal temperature of ~50 K. The satellite's spin axis is indicated; the Sun is always kept in the anti-spin direction (perpendicular to the solar array). The satellite views are courtesy of Alcatel Space (Cannes).

providing the angular resolution and rejection of stray-light; (2) a Low Frequency Instrument (or LFI) – an array of tuned radio receivers, based on HEMT amplifiers, covering the frequency range 25–80 GHz [1], and operated at a temperature of 20 K; and (3) a High Frequency Instrument (HFI), consisting of an array of bolometers operated at 0.1 K and covering the frequency range 90–1000 GHz.

The major elements of the Planck payload and their disposition on the spacecraft can be seen in Fig. 1.

3. Programmatic

Planck was selected as the third Medium-Sized Mission (M3) of ESA's Horizon 2000 Scientific Programme (http://sci.esa.int/home/ourmissions/index.cftn). Planck was formerly called COBRAS/SAMBA. After the mission was selected and approved (in late 1996), it was renamed in honor of the German scientist Max Planck (1858–1947), Nobel Prize for Physics in 1918. Planck will be launched together with ESA's Far-Infrared and Submillimeter Space Observatory (Herschel) in February of 2007.

[1] Funding shortfalls within the LFI Consortium have forced to delete the originally present 100 GHz channel from the LFI baseline configuration.

Starting in 1993, a number of technical studies laid the basis for the issue in September 2000 of an Invitation to Tender (ITT) to European industry for the procurement of the Herschel and Planck spacecraft. From the submitted proposals, a single prime contractor, Alcatel Space (France), was selected in early 2001 to develop both Herschel and Planck spacecrafts. Alcatel Space is supported by two major subcontractors: Alenia Spazio (Torino) for the Service Module, and Astrium GmbH (Friedrichshafen) for the Herschel Payload Module; and by many other industrial subcontractors from all ESA member states. The detailed definition work began in June 2001, and is very advanced at the time of writing. A view of the current design of Planck is shown in Fig. 1.

Planck is a survey-type project which is being developed and operated as a Principal Investigator mission. In early 1999, ESA selected two Consortia of scientific institutes to provide the two Planck instruments: the Low Frequency Instrument will be developed and delivered to ESA by a Consortium led by Reno Mandolesi of the Instituto di Astrofisica Spaziale (CNR) in Bologna (Italy); similarly, the High Frequency Instrument will be provided to ESA by a Consortium led by Jean-Loup Puget of the Institut d' Astrophysique Spatiale (CNRS) in Orsay (France). More than 40 European institutes, and some from the USA, are collaborating on the development, testing, and operation of these instruments, as well as the ensuing data analysis and exploitation. The capabilities of the instruments are described in Table 1.

In early 2000, ESA and the Danish Space Research Institute (DSRI, Copenhagen) signed an Agreement for the provision of the two reflectors that constitute the Planck telescope. DSRI leads a Consortium of Danish institutes, and has subcontracted the development of the Planck reflectors to Astrium GmbH (Friedrichshafen), who will manufacture the reflectors using state-of-the-art carbon fiber technology. At the time of writing the design of the reflectors is finished, the molds needed for the layout of the facesheets are very advanced, and the reflector development is proceeding according to plans.

In parallel, the instrument development has proceeded largely according to schedule, in spite of a number of financial difficulties during 2002, which at the time of writing have been largely resolved. Some hardware subsystems are already being manufactured and tested. The first deliveries of instrument qualification models are expected in late 2003, with the flight models due in early 2005.

4. Scientific performance

The principal objective of Planck is to produce maps of the whole sky in 10 frequency channels. The currently foreseen characteristics of the two Planck instruments (see Fig. 2) are summarized in Table 1; these characteristics largely drive the quality of the final maps.

These maps will not only include the CMB itself, but also all other astrophysical foregrounds, whether galactic (free–free, synchrotron or dust) or extragalactic in origin. All 10 Planck sky maps will be used to produce a single map of the Cosmic Microwave Background anisotropies. The key that allows to reach this objective is the wide spectral coverage achieved by Planck. Each astrophysical foreground has a distinct (albeit at present poorly known) spectral characteristic. Specialized data processing algorithms (e.g., Tegmark, 1997; Hobson et al., 1998; Bouchet and Gispert, 1999) will use this information to iteratively extract the signal due to each foreground component, until only the CMB signal remains. Instrumental systematic effects (e.g., Delabrouille, 1998; Burigana et al., 1998; Maino et al., 1999), as well as uncertainties in the recovery of parameters characterizing the foregrounds will degrade the final noise level in the CMB maps.

Therefore the final scientific performance of the mission depends not only on the instrumental behavior, but also on the detailed nature of the various astrophysical foregrounds, the behavior of many systematic effects which produce spurious signals (such as straylight), and the ability to remove these signals from the measured data by means of data processing algorithms. Current estimates of the performance of Planck are based on simulations of the measurement process (e.g., Bersanelli et al., 1996; Bouchet and Gispert, 1999; Knox, 1999; Tegmark et al., 2000), which include such effects to the best of available knowledge, as well as of the signal extraction process. These simulations suggest that, the ability to extract the CMB signal from the measurements will be limited mainly by the background of noise originating in unresolved structure in the various foregrounds.

The Planck instruments are also designed to provide information on the polarization state of the CMB. Although simulations of the extraction of polarization from Planck are at a less sophisticated level than those dealing with temperature anisotropies, it is expected that Planck will be able to measure with good accuracy the angular power spectrum of the "E-component" of CMB

Table 1
Characteristics of the Planck Payload

Telescope	1.5 m (proj. apert.) Aplanatic; Temp. ~50 K; $\epsilon_{system} \sim 1\%$								
	Shared focal plane; viewing direction offset 85° from spin axis								
Instrument	LFI			HFI					
Center frequency (GHz)	30	44	70	100	143	217	353	545	857
Detector technology	HEMT receiver arrays			Bolometer arrays					
Detector temperature	~20 K			0.1 K					
Cooling requirements	H_2 sorption cooler			H_2 sorption + 4K J-T stage + Dilution					
Number of unpolarized detectors	–	–	–	4	4	4	4	4	4
Number of linearly polarized detectors	4	6	12	[a]	8	8	8	–	–
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	24	14	9.2	7.1	5.0	5.0	5.0	5.0
Average $\Delta T/T$ per pixel (Stokes I) (12 mos, 1σ, 10^{-6} units)	2.0	2.7	4.7	2.0	2.2	4.8	14.7	147.0	6700
Average $\Delta T/T$ per pixel (Stokes U, Q) (12 mos, 1σ, 10^{-6} units)	2.8	3.9	6.7	[a]	4.2	9.8	29.8	–	–

[a] The possibility of adding polarization capability is being investigated.

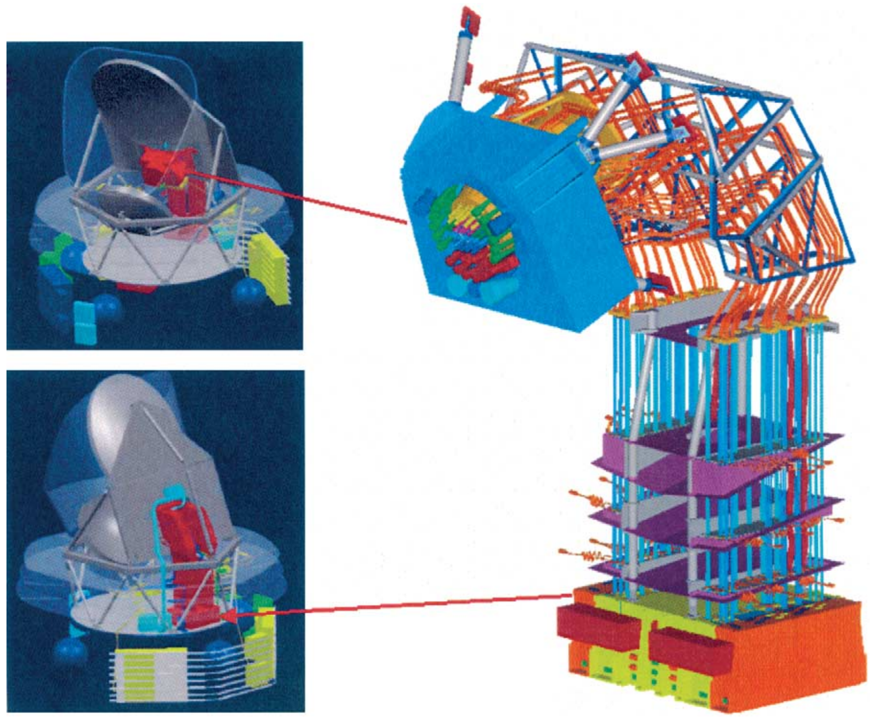

Fig. 2. On the right (top) is shown the combined focal plane unit formed by the LFI and HFI (see also Note 1 on p. 2) ; the colors on each horn correspond to frequency channels. The HFI focal plane is inserted into the ring formed by the LFI horns, and includes thermal stages at 20, 4, 2 and 0.1 K. The LFI horns and detectors are cooled to 20 K, and are attached by waveguides to a lower unit containing back-end amplifiers; a complex mechanical structure stiffens the assembly. On the left is shown the manner in which the various instrument units are distributed throughout the Payload and Service Modules. In general, all cryogenic units are located in the Payload Module and all warm units (electronics, coolers) are located in the Service Module. The figures are courtesy of Alcatel Space (Cannes) and Laben (Milano).

polarization (Hu and White, 1997), with the consequent improved estimation of cosmological parameters (Bouchet et al., 1999; Prunet et al., 2000).

Naturally, as a by-product of the extraction of the CMB, Planck will also yield all-sky maps of all the major sources of microwave to far-infrared emission, opening a broad expanse of astrophysical topics to scrutiny. In particular, the physics of dust at long wavelengths and the relative distribution of interstellar matter (neutral and ionized) and magnetic fields will be investigated using dust, free–free and synchrotron maps. In the field of star formation, Planck will provide a systematic search of the sky for dense, cold condensations which are the first stage in the star formation process. One specific and local distortion of the CMB which will be mapped by Planck is the SZ effect arising from the Compton interaction of CMB photons with the hot gas of clusters of galaxies. The very well defined spectral shape of the SZ effect allows it to be cleanly separated from the primordial anisotropy. The physics of gas condensation in cluster-size potential wells is an important element in the quest to understand the physics of structure formation and ultimately of galaxy formation.

Therefore, even though that is not its primary scientific objective, Planck will deliver high quality all-sky maps of all extended foreground emission components between cm and submm wavelengths. These maps will constitute a scientific product which is comparable to the IRAS and COBE-DIRBE maps at shorter wavelengths. The high-resolution all-sky nature of the maps, coupled with the broad spectral coverage and highly accurate calibration, will present a unique opportunity to explore in a global sense all the extended emission components of our own as well as external galaxies.

5. Mission profile

Planck will be launched together with Herschel in February of 2007 by an Ariane 5 rocket from the European spaceport in Kourou (French Guiana). Planck and Herschel will separate immediately after launch, and each will proceed independently to different orbits around the L2 point of the Earth–Sun system. At this location, the payload can be continuously pointed in the anti-Sun direction, thus minimizing potentially confusing signals due to thermal fluctuations and straylight entering the detectors through the far sidelobes.

The transit time for Planck will be between 3 and 4 months; this period will be used for commissioning of the spacecraft and instruments. The spacecraft (S/C) will be placed into a Lissajous orbit around L2 characterized by a ~4 month period and a maximum elongation from L2 of about 3,80,000 km, such that the Sun–S/C–Earth angle will not exceed 15°. From this orbit, Planck will carry out two complete surveys of the full sky, for which it requires between 12 and 14 months of observing time.

The satellite will rotate at 1 rpm around a spin axis pointed within 10° of the Sun. The payload will always remain in the shadow of the Sun. The solar array ensures this as long as it is inclined with respect to the Sun–S/C line by less than 10°. The Planck telescope and focal plane define a sparsely sampled field of view (FOV) approximately 8° in diameter around a reference line-of-sight which is inclined by 85° with respect to the spin axis. As the satellite rotates, the FOV will thus trace a circle of diameter 170° on the sky.

In order to carry out its two consecutive full-sky surveys and maintain the payload in the solar shadow, the spin axis of Planck must be displaced on the average by 1° per day in the direction defined by the orbital motion of the Earth around the Sun. This is achieved by spin axis depointing manoeuvers at regular intervals. As the spin axis is displaced, the observed circle also moves and gradually covers a large fraction of the sky.

Planck will dump each day to Earth within a period of 3 h the data acquired during 24 h. Observations will not be interrupted during the downlink period, and the S/C will not be reoriented towards the Earth. The telemetry antenna is designed to have adequate gain within a 15° half-cone from the spin axis, ensuring that even at the extremes of its orbit the Planck telemetry can achieve full bandwidth.

6. Operations and data processing

The Planck spacecraft will be controlled from a dedicated Mission Operations Centre developed and operated by ESOC in Darmstadt (Germany). From there, the scientific data produced by Planck will be piped daily to two Data Processing Centres (DPCs), which will be developed and operated by the two Consortia selected to provide the Planck instruments.

In particular, the two DPCs will be responsible for: (a) daily and long term analysis of instrument health and performance; (b) daily analysis of science data; (c) all levels of processing of Planck data, from raw telemetry to deliverable scientific products.

The two DPCs will share a basic information management infrastructure, the Planck Integrated Data and Information System (IDIS, Bennett et al., 2000). IDIS is being conceived from an object-oriented point of view, and is planned to contain five different components: (a) a Document Management Component, containing all relevant documentation; (b) a Software Management Component, encompassing the software in common between the two Consortia; (c) a Process Coordinator Component, providing a single software environment for data processing (e.g., a data pipeline manager); (d) a Data Management Component, allowing the ingestion, efficient management and extraction of the data (or subsets thereof) produced by Planck activities; (e) a Federation layer, providing inter-connection among IDIS components (e.g., relating objects controlled by each component).

The main scientific products of the mission will be produced by the two DPCs jointly, and will consist of all-sky maps in ten frequency bands, which will be made publicly available one year after completion of the mission (i.e., in late 2010), together with a first generation set of maps of the CMB, SZ effect, galactic emission (dust, free–free, and synchrotron), and point-source catalogs. The time series of observations (after calibration and position reconstruction) will also eventually be made available as an on-line archive.

7. Uncited references

Bennett et al. (1996), Mather et al. (1999), Revenu et al. (2000)

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