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ESA's Planck satellite

→ LOOKING BACK TO THE DAWN OF TIME

The science behind ESA's Planck observatory

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Only a few decades ago, the origin of the Universe was a scientific topic lacking reliable data. However, scientists now know where to look for answers, and they are steadily gaining the means to do so. ESA's ambitious Planck mission is the next step in solving many of cosmology's biggest questions.

Cosmology, the science that aims to explain how the Universe formed and evolves, has become one of the richest and hottest fields of experimental research, and experiments on the ground and in space are starting to yield new and exciting results.

Key discoveries made during the last eight decades indicate that in the past the Universe was far denser and hotter than it is now, and that it started to cool and expand – a process that is still going on today – about 13 700 million years ago. This version of events, known as the 'Big Bang' theory, is widely accepted. But the picture is still far from complete. Questions such as what triggered the birth of the Universe, or how it will evolve, remain unanswered. Named after the German Nobel-winning scientist Max Planck, one of the founders of quantum physics and noted for his research on blackbody radiation, Planck will provide the most precise and reliable data of its kind ever obtained. By doing so, it will take scientists closer to those answers, and to the origin of our Universe.

Detectives of the past and the future

Scientists trying to reconstruct an event that took place about 13 700 million years ago work very much like detectives. First they have to find the right clues, then they have to squeeze all the useful information out of those pieces of evidence. The case of the Big Bang is a long and difficult one.

It started in the 1920s, when astronomers learnt that the Universe has not always been as we see it today. They discovered that all the time, even right now, the Universe is becoming larger and larger. This means that in the past all the matter and energy that it contains were packed into a much smaller, and also much hotter, region.

Later on a second clue was identified. Scientists learnt that the stars are the 'factories' that make most chemical elements in the Universe – oxygen, carbon, iron – but also that some particular elements must come from somewhere else. They postulated, and confirmed, that those few elements had been produced during the earliest epochs of the Universe, when it was still very hot.

First light

Those findings helped to shape the Big Bang theory. But this general model describing the beginning of the Universe did not gain wide support from the scientific community until the discovery of yet a third clue.

In 1964, radio astronomers Arno Penzias and Robert Wilson serendipitously detected radiation coming from everywhere in the sky, a 'glow' filling the whole Universe with the same intensity. This radiation could best be interpreted as a 'fossil' of the Big Bang itself. The argument goes like this: if the Universe has always been expanding, then there must have been an initial period during which all existing matter and radiation were very tightly coupled together, in a high-temperature mixture.

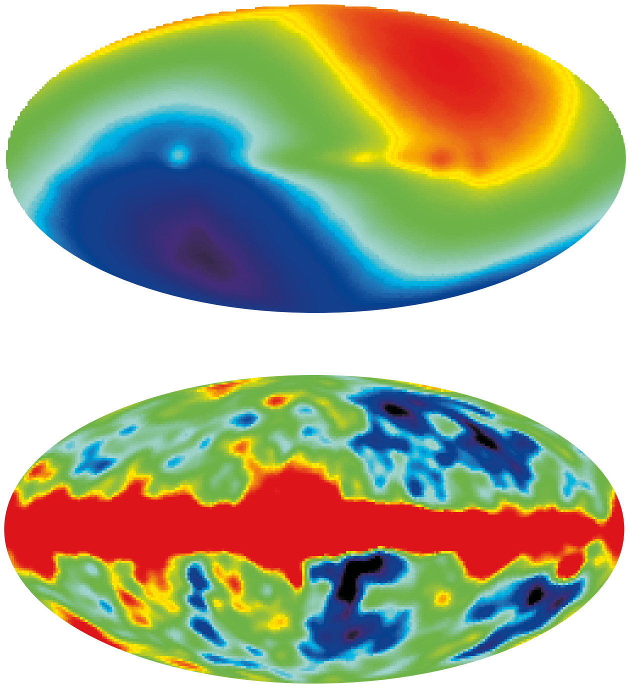
With time the Universe cooled down, and at some point it must have reached a temperature low enough for the radiation to be released from its close embrace with matter. Light would then have travelled freely throughout the Universe for the first time. That 'first light' should still be detectable today. It is, and in fact was the glow detected in 1964.

Scientists called this first light Cosmic Microwave Background (CMB) radiation. It is important not only because it is the third major piece of evidence supporting the Big Bang theory, but also because cosmologists know that they have not yet been able to extract all the information it holds.

At the time of its release, only about 380 000 years after the Big Bang, what we detect as the CMB today had a temperature of some 3000°C; but now, with the expansion and cooling of the Universe, the temperature of this radiation appears to be only a couple of degrees above absolute zero (about –270°C).

'Clots' of information

The CMB comes from every direction in the sky with almost the same brightness. But by measuring its apparent temperature all over the sky, scientists discovered that tiny differences do exist from place to place. These differences can be as small as one part in a million.



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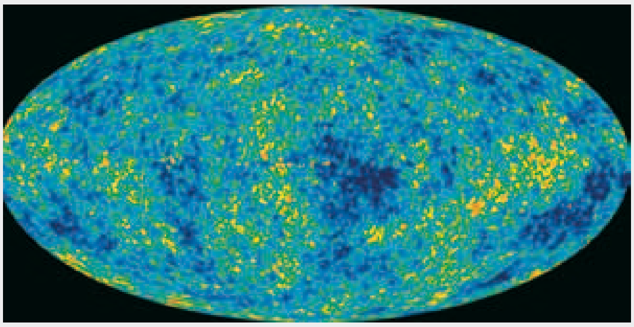
Maps of the sky as seen by NASA's COBE satellite, after different stages of image processing. The top panel shows (in false colour) the temperature of the sky after removing a uniform (2.7K) component due to the CMB; the large-scale diagonal feature (the so-called dipole) is caused by the motion of the Sun with respect to the CMB; and the faint horizontal smudge is due to emission from the Milky Way. The bottom map results when the dipole component is removed. What is left is residual galactic emission (seen as a bright horizontal band), and a background of hot and cold spots, due largely to a mixture of instrument noise and the CMB (NASA)

Although these variations may seem too small to be important, they are precisely what scientists are looking for. They are a goldmine of information. They are nothing less than the 'imprints' left in the past by matter, a reminder of the period when matter and radiation were closely coupled to each other.



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In 1992, NASA's COBE satellite confirmed for the first time that the temperature of the CMB was not uniform over the sky. In 2003, COBE's successor WMAP was able to improve dramatically the map's clarity and sharpness, showing tiny irregularities in the temperature of the CMB across the sky. This image shows CMB fluctuations from the five-year WMAP survey. The average brightness corresponds to a temperature of about -270°C (red regions are warmer and blue are colder than average by 0.0002°C) (NASA)

At that time matter already contained the 'seeds' of the huge structures that we see in the Universe today: galaxies and galaxy clusters. The tiny variations in the measured temperature of the CMB are the imprints left by those clots of matter.

In fact, much of the valuable information that the CMB can provide lies in the precise shape and intensity of these temperature variations, called 'anisotropies'. In 1992, NASA's COBE satellite obtained the first blurry signals of the anisotropies of the CMB. In 2003, its successor, NASA's WMAP, was able to chart maps that have started to reveal their detailed properties. The objective of Planck is to complete the picture by mapping these features as fully and accurately as possible.

Questions for Planck

The anisotropies in the CMB hold answers to many key questions in cosmology. Some refer to the past of the Universe, such as what triggered the Big Bang and how long ago it happened. But some other questions look far into the future. For instance: what is the density of matter in the Universe and what is the true nature of this matter?

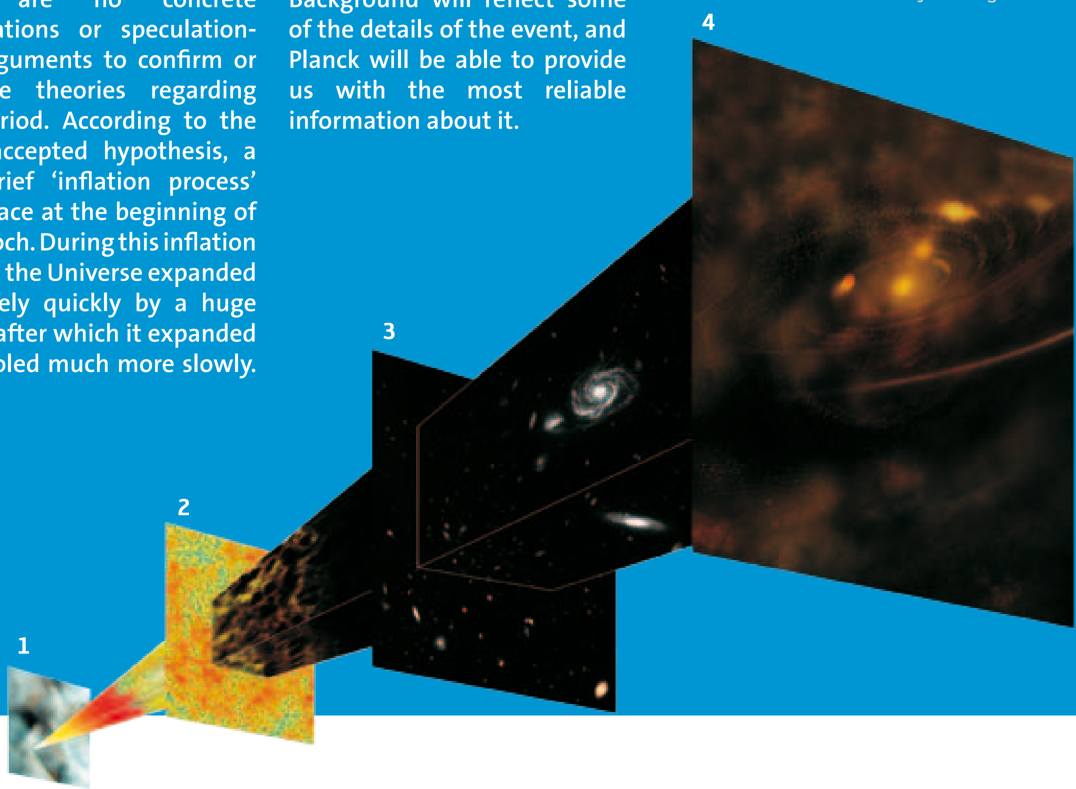
These parameters may tell us if the Universe will continue its expansion forever, or if it will end by collapsing back on itself

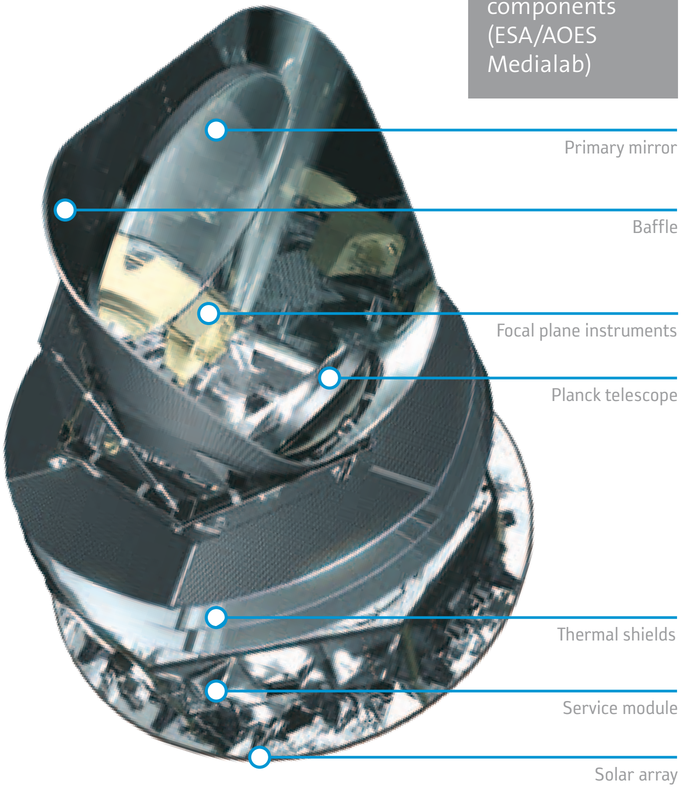
→ The birth of the Universe

The period up to a millionth of a second after the birth of the Universe is full of uncertainties: there are no concrete observations or speculation-free arguments to confirm or disprove theories regarding this period. According to the most accepted hypothesis, a very brief 'inflation process' took place at the beginning of this epoch. During this inflation process the Universe expanded extremely quickly by a huge factor, after which it expanded and cooled much more slowly.

If this hypothesis is correct, then the inhomogeneities in the Cosmic Microwave Background will reflect some of the details of the event, and Planck will be able to provide us with the most reliable information about it.

1 From one second until a few minutes after the Big Bang
2 380 000 years after the Big Bang
3 One thousand million years after the Big Bang
4 5000 million years ago





Planck main components (ESA/AOES Medialab)

in a reverse process of the Big Bang, called the 'Big Crunch'. Now, thanks to WMAP and other experiments, we know that our Universe will most likely not crunch; but new results are telling us that the fate of our Universe is stranger and less predictable than we thought. Some of the new uncertainties are related to the hypothetical 'dark energy', which may exist in large quantities in our Universe, as indicated by observations of light from distant exploding stars. What is dark energy? And what are its effects? ESA's Planck satellite will be the most powerful tool to analyse the anisotropies in the Cosmic Microwave Background, and possibly 'shed more light' on dark energy.

How will Planck work?

Planck will study the Cosmic Microwave Background by measuring its temperature variations all over the sky. Planck's large telescope will collect light from the CMB and focus it on to two arrays of detectors, which will translate the signal into a temperature reading.

The detectors on board Planck are highly sensitive. They will be looking for variations in the temperature of the CMB of about a million times smaller than one degree – this is comparable to measuring the heat produced by a rabbit on the Moon, from Earth!

The spacecraft

Planck has two main elements: a 'warm' service module, and a 'cold' payload module which includes the two scientific instruments and the telescope. The service module houses the data-handling systems and subsystems essential for the spacecraft to function and to communicate with Earth, and the electronic and computer systems of the instruments.

At the base of the service module is a flat, circular solar panel that generates power for the spacecraft and protects it from direct solar radiation. The 'baffle' is an important part of the payload module. It surrounds the telescope, limiting the amount of stray light incident on the reflectors. It also helps to radiate excess heat into space, cooling the focal plane units of the instruments and the telescope to a stable temperature of about –223°C. The baffle forms part of the passive cooling system for the satellite, before the active cooling system takes over.

The solar array, located at the bottom of the service module at one end of the spacecraft, is permanently illuminated. On the other side of the service module are three reflective thermal shields that isolate it from the payload module. These prevent heat generated by the solar array and the electronic boxes inside the service module from diffusing to the payload module.

This passive cooling system brings the temperature of the telescope down to around –220°C The temperature of the detectors is further decreased to levels as low as –273°C by a three-stage active refrigeration chain. The resulting difference in temperature between the warm and cold ends of the satellite is an astounding 300 degrees.

The coldest detectors

A key requirement is that Planck's detectors must be cooled to temperatures close to the coldest temperature reachable in the Universe: absolute zero, which is –273.15°C. The detectors on Planck have to be very cold so that their own heat does not swamp the signal from the sky. All of them will be cooled down to temperatures below –253°C, and some of them will reach the amazingly low temperature of just one tenth of a degree above absolute zero. These detectors could well be the coldest points in space.

Sharp vision

With its unprecedented angular resolution, Planck will provide the most accurate measurements of the CMB yet. The angular resolution is a measure of Planck's sharpness of vision, i.e. the smallest separation between regions in the sky that the detectors are able to distinguish; the smaller the separation, the better will be the information gathered. Planck's sharpness of vision is such that it can distinguish objects in the sky with a much higher resolution than any other space-based mission that has studied the CMB.

Planck's detectors have the ability to detect signals 10 times fainter than its most recent predecessor, NASA's WMAP, and its wavelength coverage allows it to examine wavelengths 10 times smaller. In addition, the telescope's angular resolution is three times better. The resulting effect is that Planck will be able to extract 15 times more information from the CMB than WMAP.

Broad wavelength coverage

Planck's detectors are specifically designed to detect microwaves at nine wavelength bands from the radio to the far infrared, in the range of a third of a millimetre to one centimetre. This includes wavelengths that have not been observed so sharply before.

The wide coverage is required in order to face a key challenge of the mission: to differentiate between useful scientific data and the many other unwanted signals that introduce spurious noise. The problem is that many other objects, such as our own galaxy, emit radiation at the same wavelengths as the CMB itself. These confusing signals have to be monitored and removed from the measurements.

Planck will use several of its wavelength channels to measure signals other than the CMB, thus obtaining the cleanest signal of the CMB ever. In addition, as it is monitoring signals other than the CMB, Planck is gathering data on celestial objects including star fields, nebulae and galaxies with unprecedented accuracy in the microwave, providing scientists with the best astrophysical observatory ever in this wavelength range.

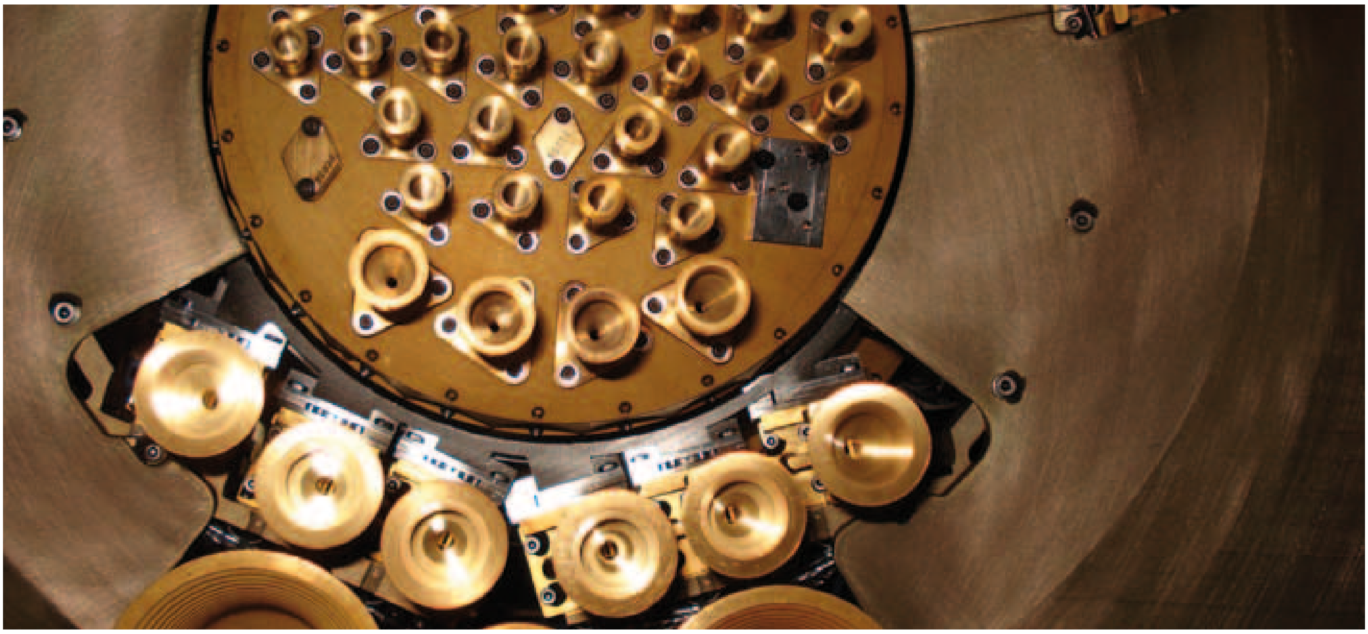
The telescope

The Planck telescope collects radiation from the CMB and delivers it to the detectors. The primary mirror, 1.9 x 1.5 m, is very large for a space mission, but weighs only about 28 kg. The mirror is robust enough to withstand the stresses of launch as well as the temperature difference between launch, when it is at ambient temperature (about –30°C), and operations (about –230°C). The mirror is made of carbon-fibre reinforced plastic coated with a thin reflective layer of aluminium.

The telescope is surrounded by a large baffle, reducing stray light interference from the Sun, Earth and the Moon, and cooling it by radiating heat into space. The telescope mirror was provided by a collaboration between ESA and a Danish consortium of scientific institutes led by the Danish National Space Centre.

The instruments

Planck carries two complementary scientific instruments: the High Frequency Instrument (HFI) and the Low Frequency Instrument (LFI). They will provide the most accurate estimates of the spatial variations of the temperature of the CMB. HFI is designed for high-sensitivity measurements of the diffuse radiation permeating the sky in all directions at six wavelength bands in the range 3.6 mm to 0.3 mm (frequencies 84 GHz to 1 THz). It consists of an array of 52 bolometric detectors placed in the focal plane of the telescope. Bolometric detectors are devices capable of detecting and measuring small amounts of thermal radiation. HFI was built by a consortium of more than 20 institutes, led by the Institut d'Astrophysique Spatiale, Orsay (France).



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Close-up of the focal plane unit during testing, showing the HFI detector array (small feedhorns in the centre) and the LFI larger feedhorns (ESA/Thales)

LFI is designed for high-sensitivity measurements of the microwave sky at three wavelength bands in the range 11.1 mm to 3.9 mm (frequencies 27 GHz to 77 GHz). It consists of 22 tuned radio receivers in the focal plane of the telescope operating at –253°C. These radio receivers will gather microwaves from the sky and convert them into an estimate of the intensity of radiation at each frequency. LFI was built by a consortium of more than 20 institutes, led by the Istituto di Astrofisica Spaziale e Fisica Cosmica, Bologna (Italy).

Several funding agencies contributed to the LFI and HFI instruments and respective data centres. The major ones are: CNES (FR), ASI (IT), NASA (US), STFC (GB), DLR (DE), NSC (NO), Tekes (FI) and the Ministry of Education and Science (ES).

Who built Planck?

Planck's design presented several technological challenges, in particular its sophisticated cooling system that keeps the spacecraft detectors at extremely cold temperatures – close to absolute zero.

ESA designed and built Planck under a common engineering programme with Herschel, ESA's infrared space observatory that will study the formation of galaxies and stars. But the two satellites shared more than just a launcher: they have undergone a joint development process aimed at optimising resources, by using the same industrial teams and shared design of spacecraft components wherever possible.

ESA's prime contractor for Planck is Thales Alenia Space France, leading a consortium of industrial partners with Thales Alenia Space Italy responsible for the service module. There are also many subcontractors spread throughout Europe and the USA. ESA and the Danish National Space Centre, funded by the Danish Natural Science Research Council, provided Planck's telescope mirrors, which were manufactured by Astrium (Germany).

→ Operating Planck

Scientific operations will be conducted by the Planck Science Office based at the European Space Astronomy Centre, near Madrid, Spain, and the two instrument teams' Data Processing Centres (DPC) and Instrument Operations Teams (IOT). Spacecraft operations will be conducted by the Mission Operations Centre at the European Space Operations Centre in Darmstadt, Germany. The Planck Science Office takes care of the scheduling of the survey strategy and the monitoring of the progress of the survey, while the instrument DPCs and IOTs are responsible for specifying the commanding and processing of the telemetry for their instrument and monitor the instrument operations. For the HFI instrument, the DPC is located at the Institut d'Astrophysique de Paris, France, and the IOT is at the Institut d'Astrophysique Spatiale, Orsay, France. For the LFI Instrument, both the DPC and the IOT are located at the Osservatorio Astronomico di Trieste, Italy.