

The Planck Mission

Advancing into new dimensions of observed cosmology

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In a few months an Ariane 5 rocket will launch ESA's Planck satellite on its way to libration point L2 together with the Herschel space telescope. At this position way beyond the Moon, Planck will map the cosmic background radiation with previously unattained precision.



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The Planck mission's 1.5-metre telescope will spend one and a half years mapping the radiation of the entire sky in the microwave range several times in a total of nine frequency bands. The mission's primary goal: to derive with a high degree of accuracy from the flood of data collected a dozen cosmological parameters for the purpose of characterizing our model of the world. In addition, totally new information about the cold interstellar matter in our Milky Way as well as in near and far galaxies will be gleaned from this flood of data. Such are the promises that are being made by astronomers with respect to new insights into the beginnings and development of the entire cosmos, and also the structure and the life of galaxies. This complex instrument owes its phenomenal capability to a sophisticated combination of new technologies.

Scientific goals, instruments and measuring technologies

Since the 1990's there have been several very successful missions which have investigated the cosmic background radiation in the microwave range, and which have made our model of the world much more plausible. What advances can we now expect from the much more elaborate Planck mission?

As little as three decades ago the status of cosmology was able to be summarised very easily: 'lots of ideas, little data'. Since that time the situation has changed dramatically, in particular thanks to a wealth of experiments that are dedicated to measuring the characteristics of cosmic microwave background radiation (CMB). The CMB is the earliest directly observable signature of the birth of the universe - its existence and its observed characteristics form one of the fundamental supports of our present cosmological view of the world.

Following the accidental discovery of CMB and the first measurement of its radiation temperature by Arno Penzias and Robert Wilson in 1965, the next step consisted of mapping the temperature of the CMB in the sky. The fluctuations turned out to be tiny. Early attempts to measure it were frustrated due to the low level of sensitivity of the instruments that were available at the time as well as due to the fact that measurements made from the Earth are affected by numerous sources of interference. After improvements were made in the area of instrument sensitivity, measurements on board an aircraft in the 1970's led to the

discovery of a dipole-shaped component of the CMB whose amplitude is around one thousandth of the average temperature. In the early 1990's the NASA satellite COBE on the one hand led to the exact measurement of the CMB spectrum and on the other hand to the discovery of the weak anisotropies at the level of one hundred-thousandth of the average CMB temperature. Both breakthroughs required measuring signals that were two to three times weaker than in their previous experiments. Both the discovery of the CMB and the successes obtained with COBE were rightly recognised with the awarding of the Nobel Prize in 2006.

After COBE, technical development in this area of research experienced a significant surge. All aspects of measurements were improved in dozens of earth-bound or balloon-transported experiments, in particular the sensitivity, the angular resolution, and the control of systematic effects. Nevertheless, space experiments play a prominent role. Observations from space are neither affected by atmospheric effects nor by emissions from the Earth's surface, offer

Fig. 1: Herschel and Planck are housed in an Ariane 5 rocket ready for launch. Soon after the launch they will continue separately on their journey.



an excellent degree of thermal stability and, if the lifespan of the mission is sufficiently long, allow the entire sky to be covered. In addition, due to their complexity and high costs, space projects operate in a very focussed manner because the scientific community uses its best efforts and expects the best results from them. The NASA satellite WMAP, whose results have continuously been published since 2003, is the most recent example of this development and sets the standard against which all further CMB experiments will be measured.

Shortly after the results from COBE appeared the Planck mission was planned jointly by the European space authority ESA, NASA in the USA and many agencies and scientific organisations in Europe and North America. As a successor to COBE and WMAP, Planck represents a new generation of space experiments in this field and thus attracts the high expectations of a pioneer experiment in a branch of research that is mature but which is still experiencing rapid growth.

The mission is named after the physicist Max Planck (1858-1957) who was the first person to succeed in analysing the spectrum of thermal radiation and who as a result established the area of quantum physics. The spectrum of the cosmic background radiation is an almost perfect example of Planck's radiation law.

In this first part of the article we describe which measurements Planck will perform, what importance this has for cosmology and astrophysics, and what technological advances and developments are necessary both in the areas of hardware and data processing in order to attain the goals that have been set.

'Sterne und Weltraum' in physics lessons



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Which processes create background radiation? What can we learn about the early history of our universe from the tiny fluctuations in this radiation? Can the temperature of the background radiation be easily measured? To answer these and other questions, simple

calculations and thought experiments can be carried out. You can read about them on the website www.esa.int/education.

We are conducting our 'Wissenschaft in die Schulen!' project in collaboration with the State Academy for Further Training of Teachers in Bad Wildbad. It is generously supported by the Klaus Tschira Foundation gGmbH.

What will Planck measure?

Our present-day understanding of the universe is based on Edwin Hubble's basic astronomic discovery in 1929 that distant galaxies are moving away from each other at a speed that is proportional to their current distance. Increasingly precise and sensitive observations made over decades have confirmed this outcome. The universe as a whole is becoming enlarged; it is expanding. Accordingly, in the distant past all of its matter must have been condensed in a very much hotter and denser state than is the case in our present surroundings. A noteworthy implication of this fact is that it should be possible to see an image of the universe in its hot initial state (Fig. 2). This is due to the fact that the speed of light is finite: we receive photons from the past when we observe distant objects. They were emitted eight minutes ago if they come from the Sun, years ago if from close stars and billions of years ago if from distant quasars. Beyond the most distant objects we plan to pick up photons from every direction of the sky that were emitted in the dense

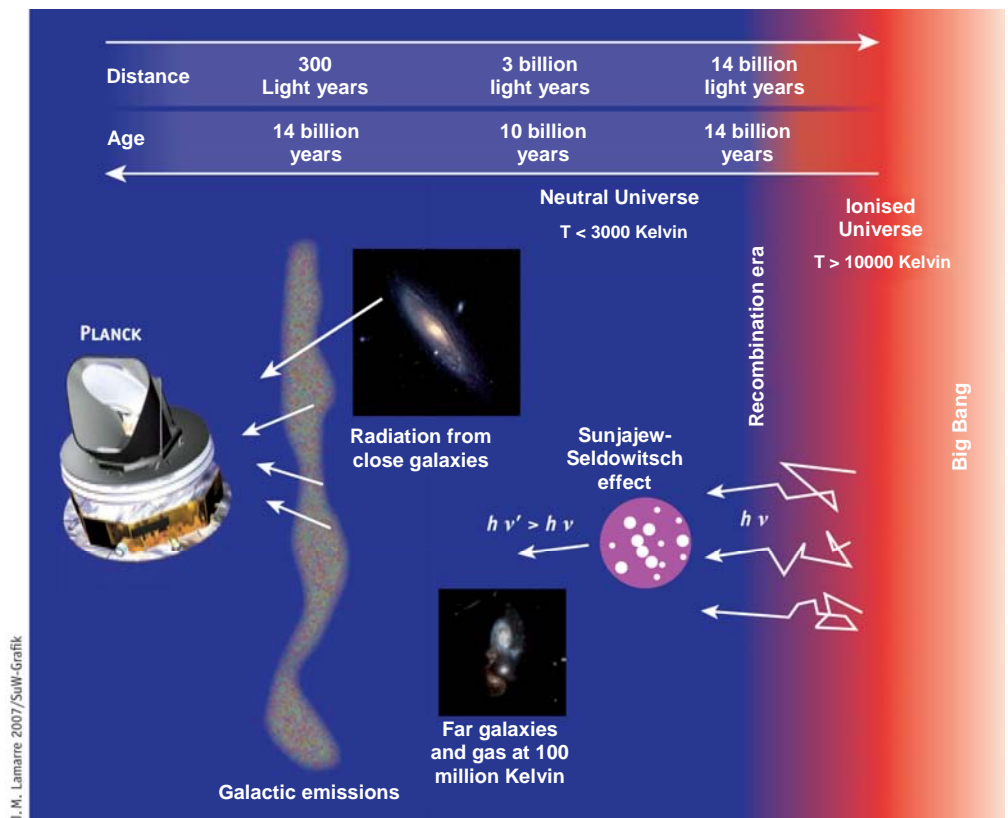
▶ Fig. 2: Shortly after its formation in the Big Bang around 14 billion years ago the universe was opaque as the photons were continually scattered towards free electrons. It was only after around 300,000 years that the universe had cooled down enough to allow electrons to combine with protons to form neutral hydrogen atoms (recombination era), and the photons were able to disperse unhindered. Due to interaction with high-energy particles the spectral distribution of the photons was modified slightly (Sunjajew-Seldowitsch effect, see also p. 50). The Planck satellite will map this cosmic background radiation - effectively the 'echo of the Big Bang' - however the signals must be painstakingly filtered out from the radiation that is also registered and which originates in 11 far and distant galaxies and in our Milky Way system.

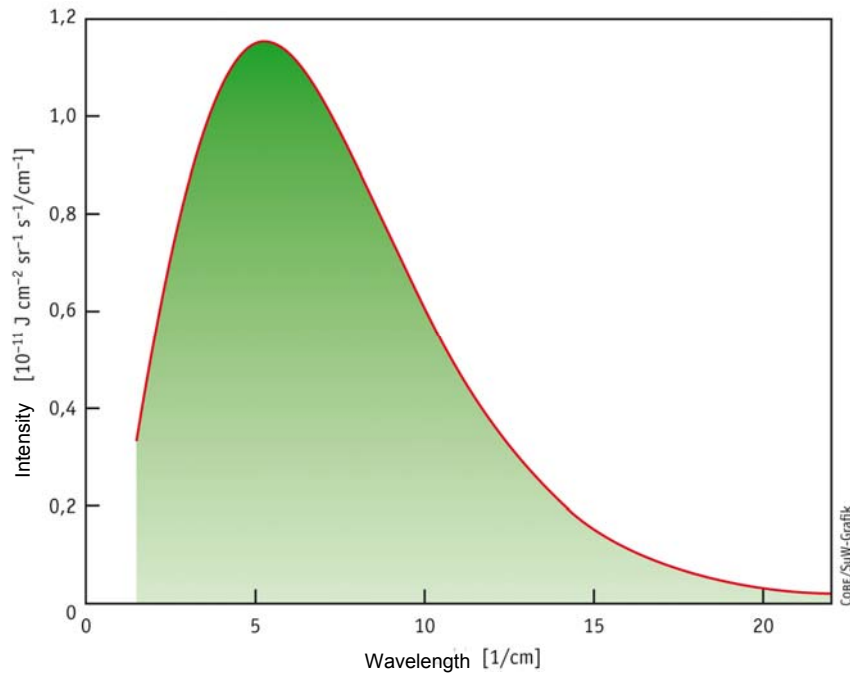
Planck - an international project

The Planck project is too large to be able to adequately recognise individual contributions. The following institutions have a high degree of involvement in the mission: the European Space Agency ESA is organising the project and financing the development of the satellite, its launch and its operation. ESA's main contract partner for Planck is Thales Alenia Space in Cannes. Industrial enterprises throughout Europe have taken part in the development of - Planck. Especially important were the contributions to the telescope mirrors by EADS-Astrium in Friedrichshafen and to the structure of the satellite by Contraves Space in Zurich. A large part of the most difficult cryogenic and optical tests were carried out at the Centre Spatial de Liege in Belgium and at the plants of Thales in Cannes.

Two consortia, each of which comprises more than twenty scientific institutes in Europe and the USA and which are supported by the space authorities of the countries involved, have developed the scientific instruments LFI and HFI and supplied them to ESA. The consortia are responsible for the scientific operation of their respective instruments and for the analysis of their data. Jean-Loup Puget

(France) is the scientist responsible for the HFI consortium that is mainly financed by CNES; in Italy, Nazareno Mandolesi heads the LFI consortium that is largely financed by ASI. NASA has facilitated the American Planck project that is located at JPL, involves scientists at many US institutes and has contributed very significantly to the efforts of the two consortia. A consortium of Danish institutes that are supported by the Danish National Research Council has participated in the development of Planck's two telescope mirrors together with ESA. The authors of this article are members of the Planck Science Team, a group of scientists representing the main partners involved in the project and who are responsible for managing the scientific aspects of the mission. The authors would like to extend special thanks to J. Aumont, M. Bartelmann, M. Bucher, H. Dole, M. Giard, B. Partridge, J.-L. Puget and M. White for contributions and detailed discussions on the topics covered in this article. C. Lawrence and F. R. Bouchet coordinated the work for significant parts of this article and made important contributions of their own. M. Bartelmann also supplied the German translation.





◀ Fig. 3: The measurements made by the COBE satellite have shown that the spectrum of the cosmic background radiation corresponds with a high degree of accuracy to the spectrum of a blackbody.

and warm primeval universe before any stars, galaxies or other cosmic structures were formed. They form the stream of primordial photons that Arno Penzias and Robert W. Wilson first observed as cosmic microwave background radiation in 1964. Together with the expansion of the universe and the primordial element frequency it forms one of the three most important experimental supports for the Big Bang theory.

Until around 380,000 years after the beginning of the cosmic expansion the temperature across the universe was so high that electrons were not able to permanently bind themselves to protons in order to form hydrogen atoms. Photons were not able to freely disperse throughout this ionised gas or 'plasma' because they were continually scattered in all directions by electrons, similar to light in fog. While the universe was expanding the plasma was cooling down. Below about 10,000 Kelvin the electrons were able to start uniting with protons to form atoms. This 'recombination' was almost complete when the temperature fell to 3,000 Kelvin. Neutral hydrogen gas is so light-transmissive that around 90 per cent of the primordial photons reach us without any further interaction despite the fact that it has taken them almost 14 billion years to reach us.

However, prior to the recombination, the photons were so closely linked to the matter that their distribution of energy directly

reflects the characteristics of the matter at that time: it very accurately corresponds to the spectrum of a 'blackbody' whose shape is solely dependent on temperature: it reflects the local temperature and density of the matter at the time of the 'last scattering'. Therefore, measuring the temperature of the CMB reveals to us the characteristic properties of the matter at that time.

While the universe is expanding the wavelengths of the photons are also increasing and the characteristic temperature of the blackbody spectrum is decreasing. The factor by which the wavelength has increased since the time at which the photon was emitted exactly corresponds to the factor by which the universe has expanded since then. And the temperature that characterises the blackbody spectrum has also fallen by this factor. Therefore the photons that were emitted by the primordial blackbody at 3,000 Kelvin were shifted to wavelengths that are larger by a factor of 1,100 and which we observe as radiation from a blackbody at 2.7 Kelvin. Measuring its spectrum using COBE showed that it deviates from an ideal blackbody spectrum by less than 0.01 per cent (Fig. 3).

This means that the cosmic background radiation appears extremely uniform (Fig. 4a). Only when the contrast

of the CMB images is intensified one thousand times can we recognise that one side of the sky is slightly lighter than the other (Fig. 4b). This asymmetry (called CMB dipole) is created as the result of the movement of the Earth and the Sun relative to the CMB (where a small part of this could still be of primordial origin). A few hundred kilometres per second are enough to increase the measured temperature of the blackbody in one direction by several thousandths of a Kelvin by way of the Doppler effect, or to decrease it in the other direction. If we remove the dipole components from the measured distribution and increase the contrast still further we can begin to recognise spatial structures on all angular scales from the largest to the smallest (Fig. 4c). These patterns reflect the state of the universe 380,000 years after the Big Bang as well as the effects of the 14 billion year-long journey that the photons have taken since last being scattered towards electrons in the primordial plasma.

In order to understand this journey we can imagine a group of photons that move freely through space after escaping from the primordial plasma. Initially the photons in the visible light have a wavelength of approximately 0.5 micrometres. Over time the cosmic expansion lengthens their wavelength and they lose energy. When they pass through a galaxy cluster they are joined by some locally emitted photons of similar wavelength which increases their number by a tiny amount. Occasionally some of the photons they come across are lost as a result of the interaction with particles. Overall, however, not a lot happens on their long journey: the universe is remarkably empty and transparent, and even billions of years later they still bear the physical information that they were stamped with when they were last scattered inside the hot primordial plasma. When their wavelengths have increased by several millimetres the photons enter the periphery of a large spiral galaxy, the Milky Way, where a few more photons from the local microwave radiation join the group.

When the photons reach their position in the Milky Way after an almost uneventful journey of nearly 14 billion years they suddenly meet a highly unexpected object: the smooth metallic surface of the Planck's

primary mirror. Their lives then end dramatically as they are collected by the Planck telescope and fed into devices into which they are absorbed.

The photons have now reached Planck's heart: the detectors - i.e. devices inside which they interact with matter and generate electrical voltages or currents that can be electronically amplified and processed to become signals. These signals are encrypted and transmitted to Earth where they reveal information to us about the origin of the photons. Some photons are lost during this measuring process. By skimming every part of the sky the Planck experiment collects an enormous quantity of cosmic photons from every direction of the celestial sphere.

After six months the sky will have been observed once in every direction so that a map of the entire sky can be generated for each detector. These maps represent the important results of Planck's observations. Using this as a basis the plan is to define the structures in the microwave background with a sensitivity and angular resolution that has never previously been achieved.

The most noticeable of these structures are the small spots with a characteristic size of around one degree (around twice the size of the full moon as seen from the Earth) which correspond to small deviations from the average CMB temperature. The first goal of the Planck mission is to measure these tiny spatial structures to gain cosmological information from them (see the box 'The angular power spectrum' on pages 44/45). In addition, Planck will touch on many other areas of astrophysics.

What can we learn from the anisotropies in the CMB?

The theory of the Big Bang that is generally accepted today indicates that our universe was 'inflated' from a primordial field and that quantum fluctuations in this field are the origin of the large-scale inhomogeneities that we can observe today. According to this model the present large-scale structure of the CMB is a warped image of the fluctuations in temperature that occurred in the first 10^{-35} seconds after the Big Bang as a result of accidental quantum processes.

Small structures have however changed considerably since the Big Bang. Initially the powerful interaction between light and (electrically charged) matter prevented the collapse of the matter in dense areas under the influence of its own gravity, and the

events were determined by the dispersal of sound waves in the primordial plasma. However, the transition from a charged to a neutral medium changed the situation dramatically (see Fig. 2). The level of energy (and accordingly the temperature of the spectrum) of the photons that were released after their 'last scattering' depends on whether they came from hot and dense or cooler, thinner areas. For this reason the pattern of hot and cold spots that was generated by the sound waves was frozen in the CMB.

At the same time the matter was freed during the recombination from radiation pressure which had previously resisted the contraction of dense clumps due to its own gravity. Under the attractive force of the gravity, the denser areas collapsed to form stars and galaxies. In fact, the fluctuations of around one hundred-thousandth of the temperature of the CMB of have the right amplitude to explain the formation of the large-scale structures that can be observed in the cosmos today.

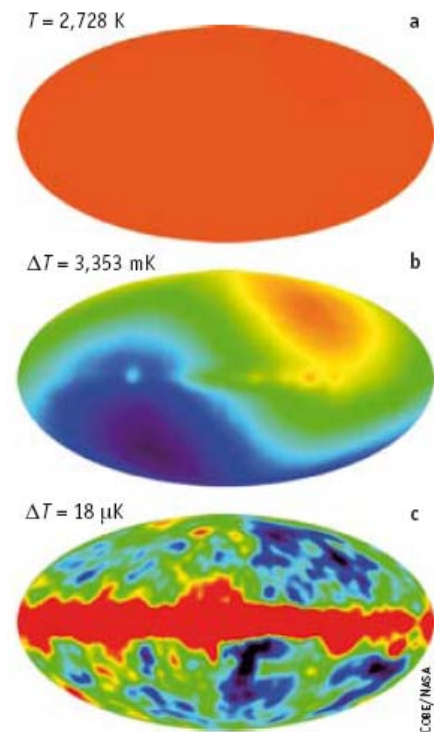
■ The physics of the primordial bang:

the small fluctuations in the CMB therefore reflect the physics of the acoustic noise in the primordial plasma shortly before the recombination. They demonstrate a characteristic pattern that is predicted in theoretical cosmology: the warm and cold spots have characteristic sizes and satisfy certain relationships to each other. These anisotropies in the CMB can be used to precisely ascertain the age, composition and geometry of the universe, to test theories about its origin and to throw light on the mysterious dark energy that we believe causes the accelerated expansion of the universe that was discovered approximately ten years ago. This process is analogous to reconstructing the assembly of a musical instrument by carefully listening to its sounds, even though the universe is turning out to be a highly remarkable instrument whose music is accompanied by several special coincidences that are crying out for an explanation.

By comparing the amplitude of the overtones with that of the base note cosmologists have discovered that the sound waves in the early universe were caused by a single short outburst and not over a longer period of time. The frequencies of the waves that we observe today look rather more like that of a tuning

fork that was hit hard once than the cacophony that ensues when repeatedly banging the lid of a pan. This undoubtedly shifts the origin of the fluctuations to the very early universe that was governed by the laws of subatomic physics.

But what caused these fluctuations? We do not really know, partly because there are many models that need to be brought into unison with the current data. These models predict fluctuations whose amplitudes and frequencies are subtly different; some favour low tones, others high. By measuring the higher overtones with dramatically increased precision it will be possible for Planck to limit the number of models that are still allowed and to provide us with information about what physical laws were at work in the first millionth of a second after the Big Bang.



▲ Fig. 4: (a) The measurements made by the COBE satellite have shown us that the omnipresent cosmic **background** radiation is distributed extremely evenly (isotropically) across the sky. (b) Only after amplifying the contrast one thousand times can the dipole components that reflect the movement of the observer (of the Sun) through the cosmic radiation field be recognised. (c) Further amplifying the contrast allows tiny but significant deviations in homogeneity to be recognised.

Cosmologists can also calculate the form and the composition of the universe from the spectrum of the CMB. Because we can theoretically forecast the spatial frequencies of the anisotropies and observe their angular size in the sky, we can estimate the distances that the CMB covers before reaching Earth. Because we exactly know the triangle that is formed by a corner where we are and two corners of successive peaks of a sound wave, we can check whether its angles add to 180 degrees and therefore carry out the classical measurement of the curvature of space that Friedrich Gauss proposed two centuries ago. Measurements such as these performed in the late 1990's showed us that space fulfils the laws of Euclidean geometry. Because Einstein's general theory of relativity predicts that the geometry of the universe depends on the density of the matter contained within it, we can conclude that the average energy density is close to its so-called critical value of 10^{-29} grams per cubic centimetre, for which critical value space is flat and it separates positively bent space from negatively bent space. But how is this total energy density distributed across its components?

The qualities of the acoustic body, i.e. the length of time that it sounds after it has been hit or what distribution of frequencies it contains, tells us about the expansion of the universe and the number of atoms that falls upon on each photon. Planck will be the first experiment to measure these qualities using the best possible accuracy. Exactly knowing the number of photons allows us to precisely measure the total number of atoms in the universe.

■ Dark matter and dark energy

On the other hand, astronomers have known for many decades that there is more matter in the universe than can be contributed to atoms. From the 'missing matter' we assume that it comprises an as yet unknown type of subatomic particle that is called dark matter. Because this dark matter interacts due to gravity, its quantity influences the sound waves. The high-precision measurement of the overtones by Planck will allow us to determine with a high degree of accuracy the total density of matter to within one percentage.

This type of precision measurement of matter density is proving to be crucial for what is a large unsolved problem in the field of cosmology: the nature of the 'dark energy', that has been named as such due to our lack of knowledge about its nature and its characteristics, and which we assume causes the accelerated expansion of the universe.

The angular power spectrum

Planck will map the fluctuation in the temperature of the cosmic microwave background (CMB) across the entire sky. Most of the information will be able to be extracted from the static characteristics of this overall picture of the fluctuations in temperature and polarisation of the CMB and shown in the 'angular power spectrum'.

This spectrum shows the percentage of the fluctuations in the overall picture depending on the angular separation between two comparative points in the sky. In the case of large angular separations the curve contains information about the physical processes that took place during the period of time immediately following the Big Bang ('Physics of the young universe' in the graphic on the right). In the case of small

angular separations its curve is determined by the 'physics of sound waves' at the time of the recombination.

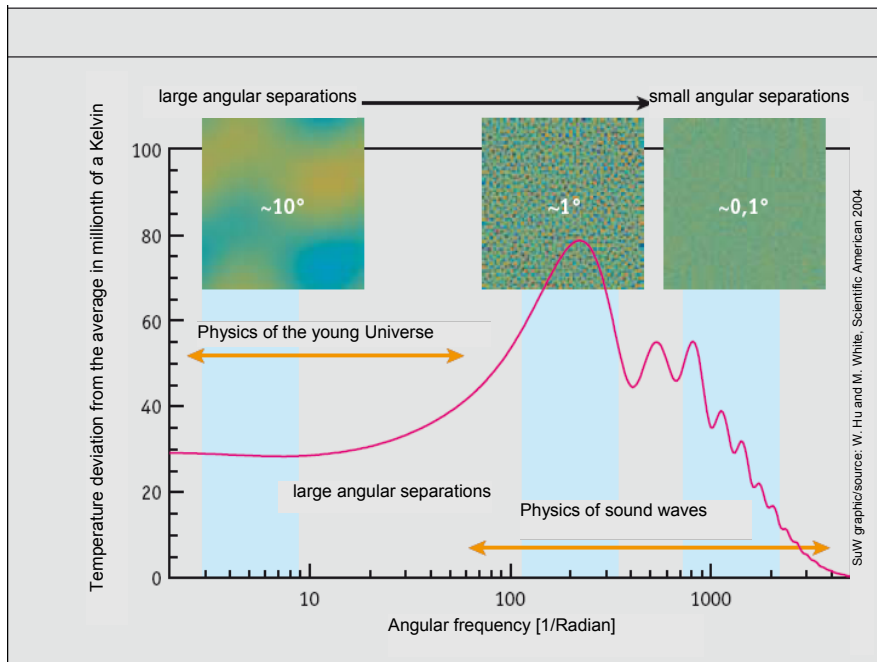
Cosmological models predict the shape of the angular power spectrum based on assumed values for a set of basic parameters that describe the characteristics of the universe (rate of expansion, geometry, age, density of matter and energy etc.). The graphic on the right shows the result of adjusting the model in this way using the data available today. Conversely, the models can be tested by comparing the measured shape of this spectrum and the true values of the parameters can be derived. Therefore defining this exactly is one of the main goals of the Planck mission. Planck will define it with an accuracy that is 15 times greater than that of WMAP.

Over one decade ago the CMB showed us that the total energy density in the universe is close to its critical value. Although inaccurate, current estimates of the density of matter nonetheless indicate that 70 per cent of this density is not able to be contributed to matter. This shortfall is consistent with independent estimations of the density of dark energy that is required in order to explain the accelerated expansion that is in turn derived from observations of distant supernovae. But more accurate measurements of the matter density are crucial if we want to ascertain the influence of each component on the rate of expansion of the universe and trace the nature of this mysterious dark energy.

Several candidates have been suggested for dark energy, but each of these suggestions has its weaknesses. The oldest harkens back to Einstein who proposed a 'cosmological constant' Λ in order to prevent his cosmological models from expanding (the expansion was still unknown at the time). As the expansion of the universe was later observed Einstein gave up this idea. Paradoxically, however, the new improved data seems to call for a cosmological constant or at any rate something similar that imitates it by way of some type of new physical mechanism. Various alternatives have been suggested.

Better data is required in order to distinguish between them or to ascertain which characteristics the right theory should have.

Planck will supply us with valuable information with regard to how we can understand dark energy that appears in two basic ways. Firstly it has accelerated the expansion of the universe over the last several billion years. The accelerated expansion suppresses the growth of cosmic fluctuations in density. This is imprinted on the anisotropies in the microwave background by way of the 'integrated Sachs-Wolfe effect'. When microwave photons fall into the depression of the gravitational field their energy becomes somewhat greater due to the so-called gravitational blueshift. If the gravitational field does not change over time this increase in energy is exactly balanced when photons later climb out of the depression. However if the gravitational field changes over time, the increase in energy and the subsequent loss of energy (redshift) can no longer cancel each other out, as a result of which an additional anisotropy is formed late in the cosmic history. Due to the long timescales that indicate the decomposition of the gravitational field in the expanding universe, this effect is especially pronounced on large angular scales. Such late distortions of the anisotropy in the CMB temperature can be differentiated from possible changes in the physics of the early universe by correlating them with gravitationally-bound structures whose existence can be inferred from other observation data Planck will also contribute to revealing the characteristics of the dark energy in a rather more indirect way by making other special experiments possible whose results would be ambiguous if they



were not analysed together with the results from Planck.

■ **Polarisation of the CMB and gravitational waves:** as well as the temperature of the CMB, photons bring us useful information in the form of their polarisations which are also correlated to the local spatial irregularities in the plasma being emitted. The CMB photons are only weakly polarised such that this characteristic is difficult to measure accurately. But the information transmitted allows us to check some of the conclusions that have been drawn solely from the temperature, thereby increasing the reliability of our interpretation. Furthermore the polarisation carries information that is still independent and which allows a more exact determination of several parameters which by means of the temperature alone could only be determined inaccurately. In particular, the polarisation contains very important traces of the processes that took place in the very first moments when the level of energy in the universe was higher than could ever be attained in any conceivable experiment. Therefore, measuring the polarisation is now a goal of most of the CMB experiments, including Planck. By examining the polarisation of the CMB we may be in a position to determine the level of energy that was generated during polarisation. For example, were the weak nuclear energy and the electromagnetic energy different aspects of the same electroweak energy, when the universe was hotter than 10^{15} Kelvin?

If the polarisation was generated at this temperature it would be an indication that the electroweak unification caused the polarisation. The cause could also however have come about at even higher temperatures or even earlier in time, perhaps when the electroweak energy was united with the strong energy, as predicted by the so-called Grand Unified Theory.

It is important when determining the energy scale that many models not only predict the fluctuations in density and pressure that disperse in the form of sound waves as the origin of the CMB, but also waves within the structure of space-time itself. These gravitational waves can extend over the entire observable universe, and their amplitude is proportional to the square of the energy level at which they were generated. By slightly distorting the surface from which we finally receive the CMB photons in our detectors these gravitational waves generate fluctuations in both the temperature and polarisation of the CMB. Planck will be well suited to measuring the large-scale polarisation anisotropies and localising the energy range in which the polarisation was generated or even just to measuring it if it is sufficiently large. Should Planck actually discover these traces it would allow the rate of expansion of the universe since the inflation to be directly determined. This would be a truly remarkable confirmation of the inflation.

How will Planck measure the radiation of the entire sky?

Thanks to a happy coincidence of nature the maximum of the blackbody spectrum of the CMB lies close to a minimum of the combined microwave emission of our galaxy and extragalactic sources. In the frequency interval between 70 and 100 gigahertz (wavelength 3 to 4 millimetres) the signals that we receive from the microwave sky aside from the galactic plane are dominated by the old CMB photons. But even in this the most transparent of all windows galactic and extragalactic sources of 'foreground radiation' contribute to the photons to a degree of several per cent. In order to recognise this astrophysical pollution and to eliminate it, CMB experiments are designed such that measurements are taken at several wavelengths in order to detect non-cosmological components by means of their divergent power spectrum.

In the case of Planck the targeted sensitivity requires highly accurate measurement of the foreground sources and this in turn requires that the measurements are made within a wide wavelength range. Simulations have shown that the scientific goals of the Planck mission can be achieved with nine observation bands that cover wavelengths in the range of one centimetre and one third of a millimetre (corresponds to frequencies between 30 and 850 GHz). This is one of the essential requirements of the instruments in the mission.

In order to record anisotropies of the temperature and polarisation of the CMB as well as their statistical characteristics with a degree of accuracy that vastly exceeds that of the earlier experiments (in particular WMAP), large advances in many areas of technology were necessary for Planck. The most important are:

■ **High degree of detector sensitivity:** the detectors must be cooled to very low temperatures in order to attain the highest possible degree of sensitivity, and this requires a very detailed probe design. Thanks to important advances in the field of detector technology and readout electronics PLANCK will be able to detect signals that are ten times weaker than those that WMAP was able to.

■ **High level of angular resolution:** Planck will be able to differentiate signals with an angular separation three times smaller than WMAP was able to. This is achieved using a larger telescope whose reflecting surface is very accurate even at very low temperatures.

■ *Wide frequency range:* Planck can receive wavelengths that are ten times shorter than those that were able to be received by WMAP. This is enabled using two different types of detectors which are optimised for different frequency ranges.

The combination of these factors will enable Planck to obtain around fifteen times the amount of information that is currently supplied by WMAP from the power spectrum of the CMB.

Such a sensitive instrument is of course affected by a correspondingly high number of interfering signals. Planck is designed to be able to control and suppress this kind of systematic effect. The selection of an orbit far from the Earth, the instrument's thermal system, the way it travels across the sky, large optical shielding plates and vibration-free coolers contribute to this, as well as a myriad of other details that have made this experiment a daunting technical challenge.

In the meantime it has to a large extent been confirmed on the ground that this technical challenge has been mastered, and Planck is well on its way to being launched in the summer of 2008. In the third part of this article (from p. 51) we will describe the most important elements of Planck's instruments and several aspects of the developments of the past ten years.

Design and operation of the space probe

The consolidation of Planck's telescope and instruments to form an enclosed system within the many and varied limitations of a space probe was a huge challenge that experienced continuous refinement over many years. With regard to the targeted never-before-achieved sensitivity, the main goal was minimising the systematic effects which must be controlled such that their impact on the detectors remains below the microkelvin level. In addition to the thermal

effects, this concerns optical pollution and scattered light, electrical interference, inaccuracies in alignment, detector couplings etc.

The first measure to control systematic effects was to operate Planck far from the Earth and the Moon, which are intensive sources of interfering thermal radiation. Planck will observe the sky from its position near the outer Lagrange point of the Earth-Sun system that is almost four times as far away from us as the Moon (see SuW 1/2007, p. 48). From this vantage point Planck can not only simultaneously turn its back to the Earth and the Moon but also to the Sun thereby always keeping the sensitive elements of its instruments in the shade. The reverse side of Planck, to which the solar cells are attached, is always irradiated and hot while the telescope and the detectors which are positioned opposite will always lie in the dark and be cooled.

In order to further decrease the temperature at the cold end and to thus keep interfering thermal radiation away from the instruments, a new type of system made from three cone-shaped reflecting surfaces ('V profiles') that are nested inside each other insulate the cold end from the warm end (see Fig 10 and 11). Thanks to this arrangement the instrument bay on Planck can passively cool to under 50 Kelvin, thereby attaining the pre-cooling level from which the active cooling steps that attain the low temperatures required for the detectors in the focal plane can be started. The difference between the warm parts of the space probe (where around 200 watts of electrical power are generated at a temperature of around 350 Kelvin) and its cold parts (where a dilution cooler removes the final approximately 100 nanowatts at around 0.1 Kelvin) illustrates the

astonishingly effective insulation properties of Planck's thermal design

Unlike most observatories that observe a large number of individual sources in the sky, Planck will observe a single all-encompassing 'object': the entire sky. In order to map the entire celestial sphere and to guarantee a stable thermal environment while doing so the probe will turn once a minute on its axis that is pointed toward the Sun. During one rotation the telescope's field of vision covers a ring with a diameter of 170 degrees (Fig. 5). This ring is repeatedly observed by all of the detectors for around 45 minutes. During this time the orbit movement of the satellite around the Sun will have ensured that the fulcrum is pointing around 2.5 arc minutes away from the Sun. This shift is corrected by periodically igniting the space probe's control jets thereby also moving the observed ring in the sky by the same angle.

In this manner the entire sky is covered within around six months. In reality the process used by Planck is a little more complicated: it must also guarantee that Planck can communicate with earth stations on the Earth at all times and that the telescope can observe some parts of the sky as often as possible. The last stipulation is required in order to monitor temporal changes in the sensitivity of the detectors.

Planck will be launched together with the space observatory Herschel on board an Ariane 5 rocket from the spaceport in Kourou, French Guiana. Minutes after the launch the two space probes will separate from the rocket and each fly alone to its final orbits around the outer Lagrange point L₂. P Planck, will reach its goal in around two months. As soon as the space probe arrives at this point it will calibrate and adjust its instruments for around two months. After this it will begin to scan the sky which is intended to be completely covered at least twice.

▶ Fig. 5: Planck rotates once a minute around an axis that is pointed away from the Sun. The field of vision is inclined 85 degrees from the rotational axis and therefore covers a circular band in the sky when rotating. While Planck is following its path around the L₂ and around the Sun this circular band covers the entire sky within six to seven months (far right).



J. Tauber/ESA/Reinhold Henkel

Aspects of data reduction

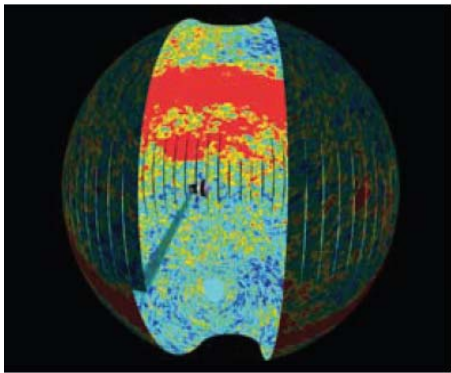
The analysis of the data collected from Planck will be an extreme exercise in 'data compression'. Planck's detectors will collect around 10^{12} measurements in the sky in order to determine around one dozen constants of cosmological importance (Fig. 6). In order to reach this goal the data must be compressed by around 10^7 times! This is to be done without introducing any perceivable systematic effects into the final results. In the process it is also expected that uncertainties regarding the cosmological constants will be able to be determined reliably. The method of 'data compression' is closely linked to the space probe's payload and its operation, and is dependent on it. All of these aspects must be designed and taken into account at the same time and with the utmost care.

Conceptually the evaluation procedure can be divided into five larger steps which however in practice are all closely related:

■ *Data cleanup and calibration.* The data is freed from many shortcomings due to the measuring process and are converted into physical units. For calibrating the data a CMB dipole is used whose amplitude and change with the orbit movement are very well known.

■ *Creating the maps.* The data is translated into maps of the sky. An optimal mathematical solution exists but requires such a high level of numerical effort that it is impossible to implement. For this reason approximate solutions must be developed that capitalise on how Planck scans the sky. They must hardly be distinguishable from the optimal solution but they must be incomparably faster.

■ *Component separation.* Our Milky Way system shines brightly over a large part of the sky, as do a multitude of other galaxies and galaxy clusters (see part 2 from p. 48). These signals will be measured and subtracted from the total signal in order to reveal the underlying CMB. The spectral distribution is crucial here: each source has its own



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spectral signature that differentiates it from the CMB. Mainly for this reason Planck will be equipped with detectors whose channels are sensitive across a wide spectral range. This allows foreground sources to be identified, mapped and separated from the CMB.

■ *Estimation of the power spectrum of the CMB.* As soon as a map of the CMB is available it is further compressed to a size of around 2,000 figures (the power spectrum) that expresses how strong the variation of the signal is on each of the angular scales contained in the map. If the models that are currently favoured for the creation of the CMB are correct, the power spectrum contains all of the information that is contained in the CMB maps. But it would be extremely interesting to find deviations from these assumptions and we will be searching intently for these. Optimal determination of the power spectrum using Planck's very large and unevenly covered maps with their more than ten million pixels requires a high computer capacity. The difficulty is providing the spectrum and at the same time a reliable estimation of the errors that are inherent in each of its data points. As is also the case when creating the maps, new methods are required here, and they are currently being developed and tested.

■ *Estimation of the cosmological parameters.* Each cosmological model forecasts a specific shape of the CMB power spectrum that will be compared with the one measured. The predictions from the models depend on assumptions and the values of a host of 'cosmological parameters' which therefore will be able to

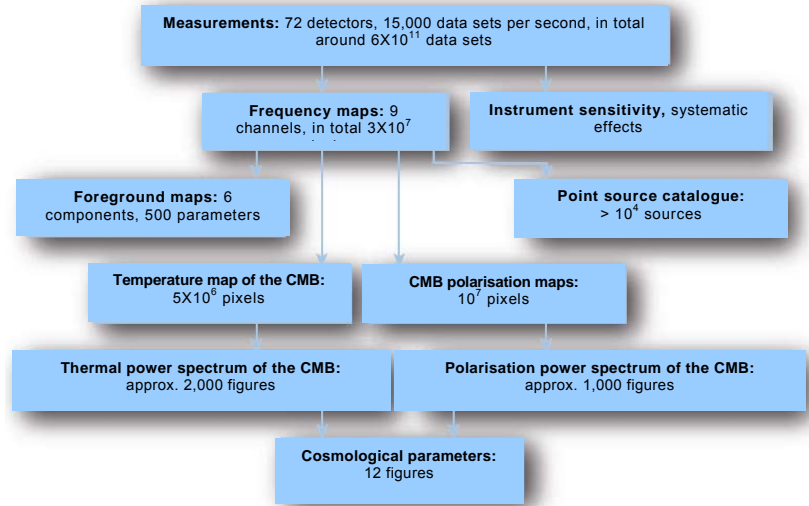


Fig. 6: At each step of the evaluation procedure the amount of data is reduced several times. Lastly the approximately 10^{12} measured data sets will be reduced to around one dozen cosmologically meaningful figures. During this data compression none of the original information can be lost and no dummy information can be simulated.

be derived from the data. It is here that scientific assessment and aptitude are most clearly a part of the entire process because of the broad area of possibilities there are to investigate. In particular, the number of parameters in a model also determines its uncertainties to a significant degree.

The above steps all depends closely on each other. In this way, for example, some instrument-related effects are only made apparent by investigating the differences between maps from similar detectors or when an energy spectrum appears distorted. Many iterations will have to be run through before every aspect of the problem is understood. For this reason the analytic process is iterative and sensitive to repercussions, and the entire process chain must be run through a number of times, with the amount of information increasing each time. It is crucial to success that the uncertainties of all of the parameters involved are determined from the beginning to the end of the analysis. We gain faith in this process by means of exhaustive simulations in which all of the input parameters of the analysis chain are known and which allow the influence of specific effects on the results to be investigated. Such simulations again require a lot of effort.

However, the principle of the analysis will be: only trust a new or surprising result after it has been extensively tested by several teams using several methods! There is no foreseeable end point of the data evaluation that can be stated at the beginning. Rather, it will be iterated for the whole chain until no major open issues remain and the results can be regarded as solid and ready for publication in scientific literature.

Outlooks

With its many times higher observation capacity the Planck mission will lead to a dramatic, perhaps revolutionary advance in our understanding of the universe. In addition it will significantly influence other areas of astrophysics and leave a long-lasting legacy. The instruments and evaluation procedures which are to be used to record and process the Planck data have been developed and tested. The rest will depend on nature, which undoubtedly has some interesting surprises in store, and on the resourcefulness of the participating teams which has already been tried and tested at length over the past decade of preparation.

There are many ways in which Planck will tap into new areas within the astrophysical community. According to the number of scientists and scientific institutes involved, PLANCK is one of the largest experiments ever undertaken in the field of astrophysics and will bring them closer to the world of high-energy physics both in terms of the topic and the approach. The organisation of this experiment, with its diverse community that spans many different institutes, countries, authorities and cultures, is just as large a challenge as building the instrument and evaluating the data.

According to the current plan, Planck and Herschel will be launched in the summer of 2008 and if all goes well the first cosmological results will be able to be published in 2012. □

How Planck sees the sky

During its repeated comprehensive coverage of the entire sky the Planck telescope will not only record the microwave radiation of the cosmic background but also that of many other sources. The most important of these are described below.

In Fig. 7 the energy spectra of all of the sources that contribute to radiation from a 'typical' direction in the sky are plotted. The background in the visible and near infrared is made up of numerous distant galaxies that can be individually recognised in the deep scanning pictures made by the Hubble and Spitzer space telescopes. But the background in the distant infrared and millimetre-wave range - with the exception of the very brightest sources - has not yet been able to be broken down into individual sources. Half of the star formation in the history of the cosmos, which took place in the brightest infrared galaxies at a high level of redshift, still remains mostly hidden to astronomers! Planck is the most powerful measuring device built to date for the purpose of investigating the structures in the background radiation in the millimetre and submillimetre range, in which the longwave (redshifted!) part of the infrared background radiation also lies.

The Milky Way

The galaxy in which our Solar System is located will provide Planck with a rich mix to observe. From our position near the main plane of the Milky Way system the galaxy appears as a narrow band that runs across the entire sky in the form of a great circle (Fig. 8). Due to the interstellar dust that has been generated by late star types and supernovae the Milky Way is impermeable to visible light in distant areas. However, this 'dark' dust becomes perfectly penetrable in the infrared and submillimetre range and itself emits in these spectral ranges according to its temperature. Planck will see substantial emission of gas, dust and energy-rich particles in the thin disc of our Milky Way.

The three dominant sources of this diffuse emission are (see Fig. 9): (a) interstellar dust in the galactic disc that primarily emits thermal radiation; (b) electrons that spiral around magnetic flux lines at almost the speed of light; and (c) electrons that interact with matter and emit so-called braking radiation in the process. Planck will for the first time simultaneously map these sources. In addition Planck will map the polarisation of the galactic emission, thereby providing us with access to new physical phenomena. Thus it will for the first time become possible to map the three-dimensional structure of the galactic magnetic field that is one of the main polarising sources in the Milky Way.

In addition to the diffuse emission Planck will see many point sources in the Milky Way. Included here are very young areas of star formation, compact areas made of ionised hydrogen and supernova remnants. Objects in our Solar System - planets, asteroids and comets - will also be able to be seen on the Planck maps. This rich mix of diffuse and point sources will make it difficult to separate the individual components, but the result will keep the community of scientists occupied for decades.

Other galaxies

There are billions of other galaxies in the universe, many of which resemble our Milky Way system, but many of which are also radically different from it. Many of these galaxies glow (as ours does) in synchrotron light and in the light of the thermal emission of its warm dust. Planck's longwave instruments will discover thousands of radio sources (the majority of which emit at wavelengths that are typical for synchrotron radiation), and Planck's shortwave instruments will find around ten thousand dust-rich galaxies.

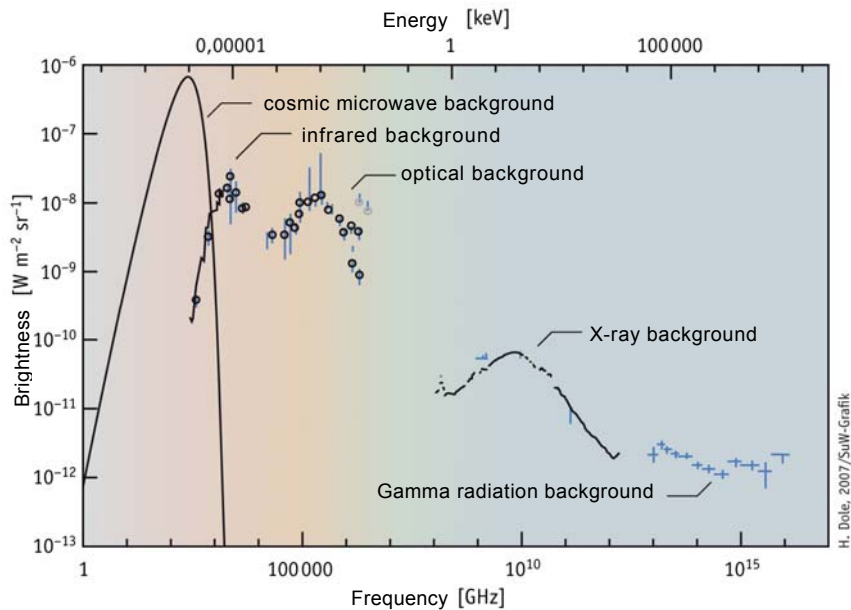


Fig. 7: This curve shows a typical frequency spectrum of one of the 'cleanest windows', far from the bright Milky Way band and from interstellar clouds. The spectrum shows the average electromagnetic radiation in the universe depending on the frequency; the data used originates from a multitude of observatories, most of which are in space. Of the total energy, 95 per cent is contained in the CMB. The remaining five per cent is located in the radiation emitted by all galaxies since their formation and is approximately evenly distributed across the visible and near infrared (maximum at a wavelength of two micrometres) and the far infrared (maximum at 200 micrometres). X-radiation and gamma radiation contribute to only around one hundredth of a per cent and radio background to only one millionth of the energy of the entire electromagnetic radiation.

The radio sources that Planck will discover will probably be special in that they flicker or are especially young and therefore have a high-frequency synchrotron spectrum. Most of these radio sources will be relatively close to us in a cosmological sense: in the case of redshifts we expect them to be smaller than around one.

In contrast the dust-rich galaxies that Planck will discover at shorter wavelengths could be very much further away. Due to the redshifting, if we use the same wavelength for observation we reach increasingly shorter wavelengths as the distance increases, and therefore the observed spectrum of the sources of thermal emission changes abruptly. For this reason Planck can recognise dust-rich galaxies with very sizeable redshifts. We even hope to find thermal emission from mass-rich galaxies that are currently being formed at redshifts of 5 to 10: these objects will be observed as they were less than 1.5 billion years after the Big Bang, i.e. after one-tenth of the current age of the world! Because the galaxies that were first formed probably had the greatest tendency to form groups, we hope to find groups of this kind of 'primeval galaxy' using Planck.

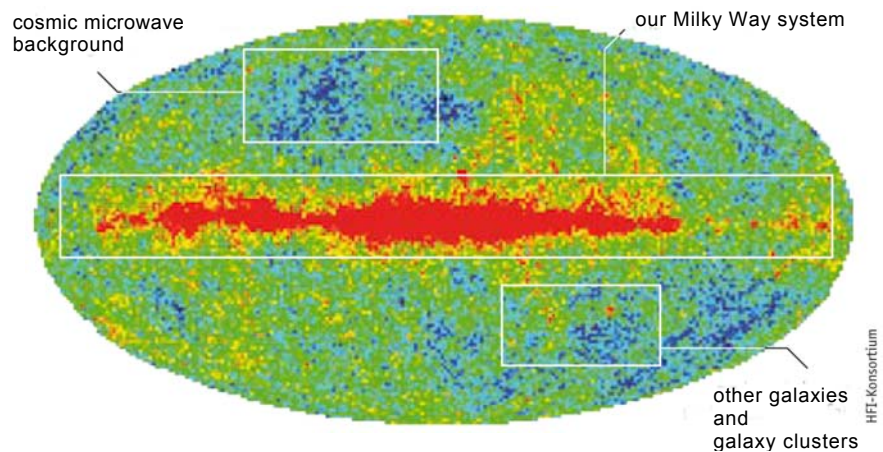
But most of the distant galaxies by far will remain indiscernible for Planck as individual sources. Instead their superimposed emission will contribute to a diffuse background that stretches almost isotropically across the entire sky. This undispersed emission from distant galaxies is called cosmic infrared background. Planck will be able to investigate the large-scale distribution of the star formation activity and significantly contribute to our understanding of the formation of galaxy clusters.

Galaxy clusters

On their long journey towards us the photons in the CMB traverse inhomogeneities in the distribution of matter and cosmic structures that stamp them with weak but important information. Among the most interesting events that could happen to a CMB photon are encounters with hot electrons and diversions through gravitational fields.

The largest gravitationally bound structures in the universe are the galaxy clusters. They contain several hundred to approximately one thousand galaxies that are held together by the gravitational force of up to 10^{15} Sun masses, to which the dark matter makes the greatest contribution. The galaxy clusters are charged with a diffuse, ten to one hundred million-degree gas - at these temperatures electrically neutral atoms cannot exist: they will split into their electrons and

Fig. 8: The tiny fluctuations in intensity that Planck is expected to measure (shown here in a model) only become visible in the maps created after the average temperature radiation of the CMB and the 'dipole' have been subtracted. The remaining dominant component is the emission from our own Milky Way. Further away from the galactic plane most of the structures that are larger than around one degree are anisotropies in the CMB. However the emission of distant galaxies and galaxy clusters is buried beneath them. Every object of this type possesses its own characteristic spectrum which allows it to be differentiated from the others.



nuclei and form a plasma.

On their path through a galaxy cluster CMB photons are occasionally met by one of these electrons whose energy is much higher than that of the photon. In doing so the photon is brought to a considerably higher level of energy. As a result the number of low-energy photons decreases and that of the high-energy photons increases. At low energy levels or frequencies the galaxy cluster weakens the microwave background; it throws a shadow, so to speak. But the scattered photons reappear at higher frequencies where the same galaxy cluster appears as a source of light. This is the so-called (thermal) Sunjajew-Seldowitsch effect. For almost all types of galaxy clusters at

any distance the crossover frequency between light and shadow lies at 217 GHz (1.3 mm wavelength), in the middle of the frequency range that is covered by the detectors on PLANCK.

Despite their huge size galaxy clusters appear as small objects in the sky. Planck cannot resolve most of them. Nonetheless they will be easy to discover in the Planck data because of their unique signature that is generated due to the Sunjajew-Seldowitsch effect. No other known source throws a shadow below 217 GHz and glows above it! A further advantage of the Sunjajew-Seldowitsch effect is that it has only a weak dependency on the distance of the galaxy cluster. Even very distant galaxy clusters can be found in this way if they exist. Almost 10,000 galaxy clusters are expected to be able to be found in the Planck data, of which around one hundred will be very distant. This fact alone is already very exciting as galaxy clusters can be regarded as guide fossils of cosmology. They develop late in the cosmic history and the era of their formation and liveliest development is highly dependent on the cosmological parameters. In this way the cosmological parameters can be independently checked by means of the population of the galaxy clusters that will be found in the primary Planck data. But the population of the galaxy clusters is supposed to also be able to reflect the characteristics of the mysterious dark energy that is responsible for the accelerated expansion of space. Thus the galaxy clusters that are to be discovered by Planck will exhibit their

own individual cosmological source of information, and even more so when the measurements of the Sunjajew-Seldowitsch effect are combined with those in the optical, infrared or X-ray range.

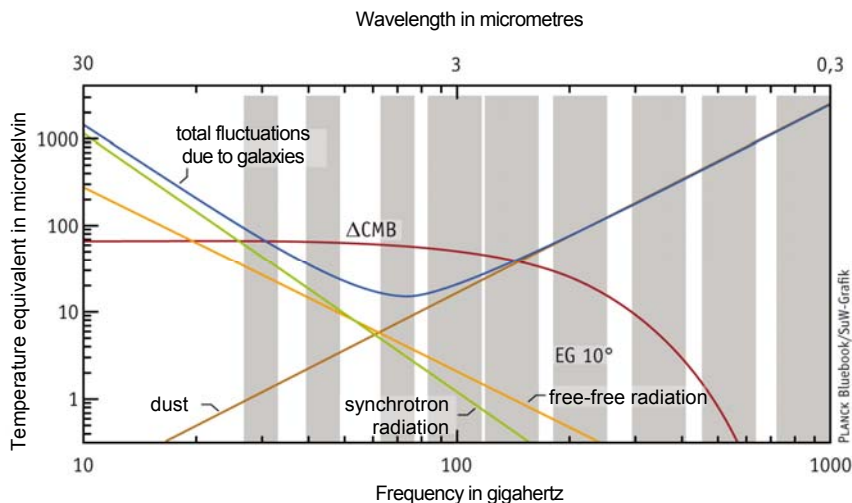
During a period of time that was short by cosmological standards at the beginning of their journey the CMB photons disperse in neutral gas. After the first stars and other astronomical sources were formed their energy-rich radiation ionised the surrounding gas again and separated the electrons from their nuclei. Photons cannot freely disperse in ionised material as they are continuously scattered by the free electrons, similar to the Sunjajew-Seldowitsch effect. Depending on when and how this re-ionisation took place it must have changed the appearance of the CMB. It is quite possible that the history of the re-ionisation will also be able to be reconstructed using the Planck data.

Einstein found that masses divert light. Therefore the CMB photons will be diverted while they disperse throughout the universe when they pass through cosmic structures. The observation of the CMB using the large-scale structures of the universe can therefore be compared to observing lights through fluted glass: it is distorted. Of course we do not know how the CMB would look without this gravitational lensing. But the patterns that stamp the gravitational lenses on it have certain characteristic properties that allows them to be able to be detected in the data. On the one hand they interfere and must be removed from the CMB maps before exact conclusions can be drawn regarding the universe. On the other hand they provide us with highly valuable information about the distribution of mass in the universe on large scales. Besides smoothing the CMB structures, gravitational lenses also effect additional structures in the polarisation of the CMB which it could not have alone.

A further effect that is closely connected with gravitational lensing concerns the development of structures while the CMB photons fly through them. Because for example galaxy clusters have diameters of several million light years they are able to continue developing significantly while light is travelling through them. When the photons enter galaxy clusters they gain energy by falling into the gravitational potential, and they lose energy when they exit again. If the gravitational potential deepens while the photons are inside it they lose more energy when exiting than they gained when entering. This effect that also occurs on even larger scales than galaxy clusters will also be included in the Planck data.



Fig. 9: Spatial fluctuations in the intensity of the CMB (crimson line) depending on the frequency, compared with the fluctuations of the intensity of other sources of microwave radiation. The emission of the galactic interstellar dust, synchrotron radiation from free electrons and free-free radiation are shown according to measurements made by the space probe Wmap (Bennett et al. 2003). The strength of the fluctuations in the CMB and in the galactic emissions depends on the observed angular separation; here they are shown for a separation of one degree. For small angles the extragalactic sources dominate. The minimum of the diffuse foreground emission and therefore the least disturbed window onto the fluctuations of the CMB are around 70 GHz. The grey bars show the frequency ranges in which Planck will make its measurements.



How Planck works

The high degree of sensitivity and stability of the measuring instruments of the Planck mission has been achieved thanks to completely new technological developments. Here we will highlight their main aspects.

The telescope

In order to achieve an angular resolution of around ten arc minutes in the cosmological window that is close to three millimetres wavelength (corresponding to a frequency of 100 gigahertz) the opening of the telescope (Fig. 10 and 11) must be around 1.5 metres. The telescope is optically designed such that it minimises interferences from sources that are outside its field of vision. The primary and the secondary mirror are elliptical and attached such that the radiation that enters is not shadowed by mirror edges and mechanical parts. Similar 'skewed' optical arrangements have already been used in earlier CMB experiments.

Because it was necessary to house many detectors for a wide frequency range inside Planck, the design had to be planned very carefully. The mirrors are made of carbon fibre reinforced plastic in a honeycomb-like layer structure that is coated with a thin layer of aluminium. These mirrors are suited to Planck's space environment, they ensure a high degree of reflectivity (> 0.995), are light, have few mechanical surface irregularities (typically in a range of five micrometres) and are stable in the face of thermal stresses. For example the main mirror measuring 2×1.5 metres weighs only 28 kilograms, but is nonetheless rigid enough to withstand the force of the launch. Its shape remains virtually unchanged when the launch temperature of 300 Kelvin drops to 40 Kelvin during operation.

At the wavelengths that Planck observes, diffraction effects are important. They generate diffraction patterns that do not disappear even with large degrees of angular separation from the optical axis. Scattered light that reaches the detectors from directions far from the line of sight represents an especially serious problem for CMB experiments. In the microwave range the CMB has only around one per cent of the luminosity of the Earth such that experiments in orbits that are close to the Earth are especially susceptible to this interfering radiation. Only in orbits far from the Earth can this effect be diminished to a large degree as there the solid angle under which the Earth appears decreases drastically.

This is one of the main reasons why orbits around the libration point L2 were selected

for WMAP and Planck (see SuW 1/2008, p. 48).

Seen from from L₂ the Earth appears as large as the full Moon appears from Earth. But Planck's high degree of sensitivity requires that even at L₂ the scattered light must be extremely effectively shielded - the tolerance limit is at around one millionth; prior to Planck it had never been achieved. In order to suppress the scattered light effectively, the instrument optics cover only a small part of the telescope which moreover is surrounded by large shielding plates. A comprehensive series of tests (which attained never-before achieved levels of accuracy) ensured that the necessary suppression of the interfering radiation had really been achieved. Sophisticated software which takes into account all aspects of the optics was used in parallel to calculate exact models of the optical path and compare them with the measurements for each of the - detectors. This precise monitoring of the optical characteristics by means of calculations and laboratory data corresponds to the most advanced technologies in the field of microwave antennae.

The instruments in the focal plane

The Planck telescope steers photons from a small section of the sky onto the focal plane. The first components that the photons meet there are the horn antennae (Fig. 14 b and c). These are resonant antennae that pick up the microwave radiation with an extremely exactly defined angular resolution and thus enable scattered light and directional sensitivity to be very exactly controlled. After passing the horn antennae the fate of the photons essentially depends on which type of detector they fall into.

In the millimetre wave range there are two main types of detector technology. One is based on coherent radio receivers whose concept is similar to that used in WMAP and COBE, but was already used by Penzias and Wilson when they discovered in the experiment when they made the discovery in the mid 1960's.

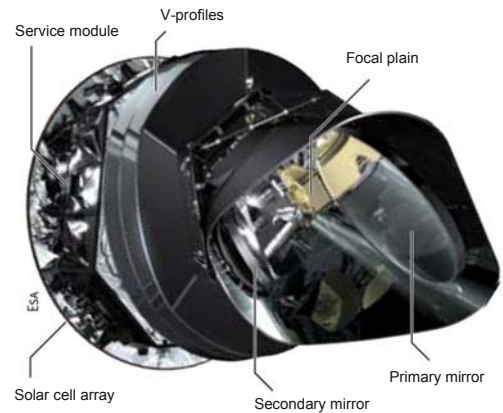
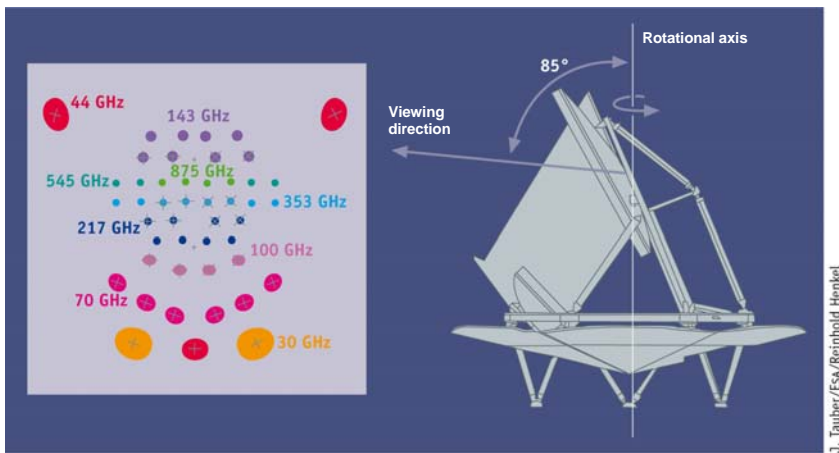


Fig. 10: The scientific payload of the Planck mission comprises the telescope's primary and secondary mirrors as well as two measuring instruments. The majority of the measuring instruments lies close to the focal plane of the telescope, but most of its components are distributed across the entire probe and cannot be seen in this picture. The most important parts include the cooling units that bring the detectors to their extremely low temperatures.

Fig. 11: The Planck telescope collects the radiation from the sky and bundles it in the focal plane. It is a total of three metres high and three metres wide, and its two aluminised mirrors consist of carbon fibre reinforced plastic.





◀ Fig. 12: The areas measured by the detectors form a very loose pattern (left) and are located in the sky staggered by 85 degrees to the rotational axis of the space probe.

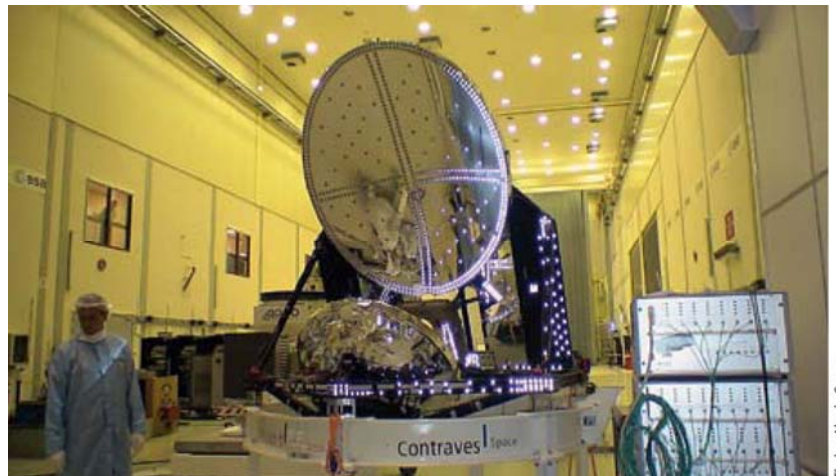
▼ Fig. 13: Planck's telescope is being prepared to make measurements in a cold state.

The other is based on bolometric detectors with filters which are cooled to extremely low temperatures and are similar to those that have been used in a range of balloon experiments. Neither of the two technologies has as yet demonstrated that it is able to achieve the necessary measuring accuracy within the entire spectral range that is covered by Planck. For this reason Planck uses both technologies at their respective operational optimums. The low-frequency instrument (LFI) is an arrangement of radiometers that are cooled to 20 Kelvin and cover three frequency bands between 30 and 70 gigahertz. The high-frequency instrument (HFI) consists of bolometers that are cooled to 0.1 Kelvin and cover six bands between 100 and 850 gigahertz. Together with the telescope these detectors represent a previously unattained combination of sensitivity, angular resolution, wide spectral range and sky coverage.

■ The low-frequency instrument LFI

Radiation with wavelengths larger than three millimetres is fed into the LFI (Fig. 15). It meets suitable waveguides that separate the two orthogonally linear polarisation sections from each other. Each polarisation channel is connected to its own radiometer in order to retain all of the information about the intensity and the linear polarisation of the photons that enter it. A major advantage of coherent receivers is that they are able to very accurately separate the two polarisation directions from each other, leaving a mixture in the region of only 0.01 per cent.

The radiometers start with multi-stage HEM transistors (HEMT - high electron mobility transistor) that amplify the signal by around ten million times. In a HEMT the conduction electrons are limited to two-dimensional layers, decreasing the scattering and increasing the mobility of the electrons, and as a result the noise level becomes very low. Planck uses last generation indium



phosphide HEMTs which have gate lengths of only 50 nanometres. The intrinsic noise of a HEMT is considerably reduced if it is operated at very low temperatures. To optimise its performance the entire entry end of the LFI is cooled to 20 Kelvin. A further advantage of indium phosphide HEMT's is their lower energy consumption which is a significant requirement for operating cryogenic experiments in space. The whole arrangement of 44 amplifiers in the LFI uses less than 0.5 watts.

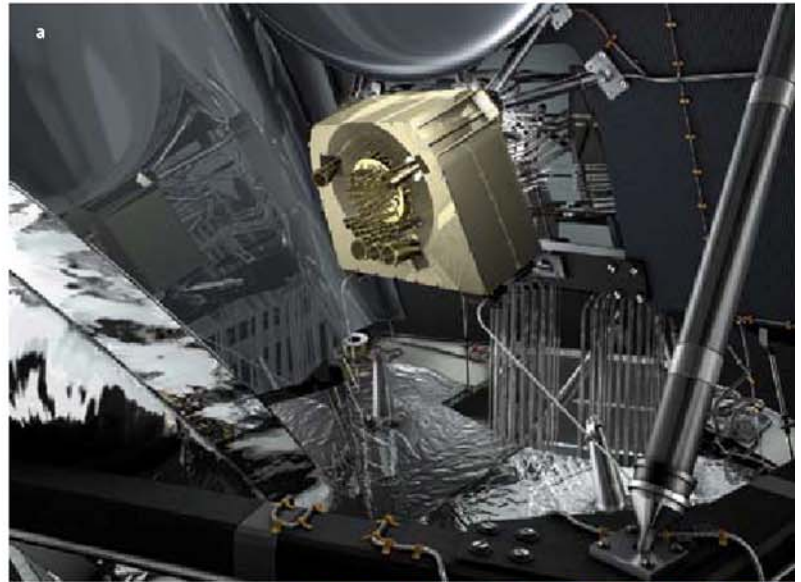
The disadvantage of the HEMT amplifier is that they introduce an additional source of low-frequency noise (so-called 1/f noise). In order to suppress its impact the celestial signal is continually compared with an internal reference source (a blackbody at four Kelvin). This is done by fitting devices both in front of and behind the amplifiers, allowing the celestial signal to be mixed with that of the reference source.

In this way both signals experience the same interferences from the two parallel chains of HEMT's. When the difference of

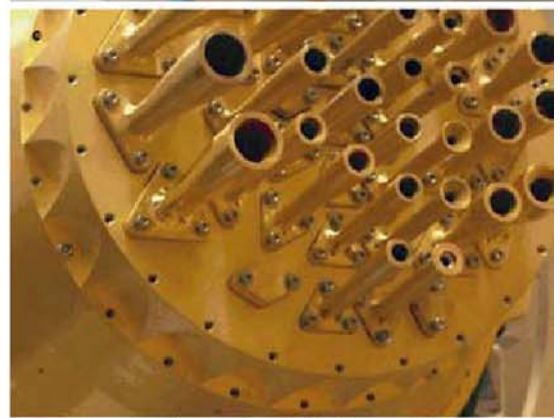
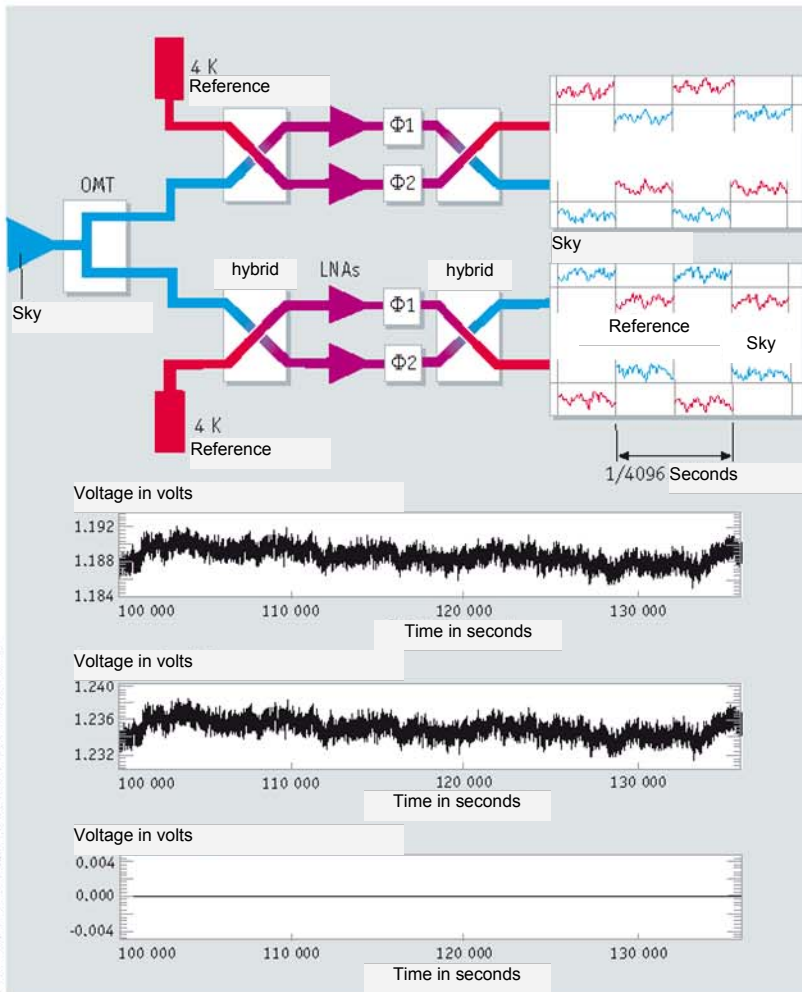
the two is formed (Fig. 15 below), these interferences disappear and the signal becomes around ten thousand times more stable than if only one chain were used. The remaining interferences in the measured signal are further reduced by the process of the space probe sensing the sky, which enables a comparison of measurements at intervals of one minute.

The signals are then sent through waveguides that are approximately one and a half metres long which connect together the cold (20 Kelvin) and the warm (300 Kelvin) parts of the instrument. After being further amplified one thousand times the signals are registered by a detector diode. In order to suppress additional instabilities that arise due to the warm electronics a phase switch switches between the celestial signal and the reference signal 4,000 times per second. The direct current voltage at the detector's output is amplified, integrated, digitalised, compressed, and sent to the earth station. All of these measures serve to ensure the stability of an instrument that microkelvin signals must discover in a background that is around one million times brighter.

▶ Fig. 14: (a) A model of the focal plane configuration. (b) The focal planes of the low-frequency instrument (LFI); The entire unit is cooled to 20 Kelvin by a sorption cooler. The horn antennae are recognisable at 30, 44 and 70 gigahertz (in decreasing order) as are some of the 70 gigahertz modules and waveguides. The central cavity will house the high-frequency instrument (HFI). (c) In the focal plane of the high-frequency instrument, horn antennae of different sizes cover six frequency bands in the range of 100 to 850 gigahertz. This part is cooled to four Kelvin by a Stirling cooler as a pre-stage for the bolometer that is cooled to 0.1 Kelvin. (d) The integrated low-frequency and high-frequency instrument after creating the connection with the space probe. The focal plane lies on the downward-facing plate.



▶ Fig. 15: Above - Diagram showing the signal path through a LFI radiometer chain (input stage). Below - the measured signal, the reference signal, and their difference. The stability of the difference signal is 10,000 times higher than the individual components. The LFI contains eleven horn antennae that are connected to a total of 44 detectors.



A. Mennella und F. Villa, LFI-Kollaboration/Rheinhold Henkel

C. Carreau/ESA

The LFI has been laboratory-tested in various stages from its individual parts to the whole system. In the process sensitivity values that meet expectations and a degree of stability that exceeds the optimistic forecasts were yielded.

■ The high-frequency instrument HFI

Radiation with wavelengths shorter than three millimetres are fed into the HFI. The exact frequency range is defined by interference filters that are designed such that warming due to radiation is insulated and not passed on internally. Depending on the type of bolometer, a given polarisation direction is either selected or not. The photons selected are then absorbed by the bolometer because the electromagnetic wave that is entering stimulates electrons in a damped absorber where the movement of the electrons is converted into heat due to the damping. This heat increases the temperature by tiny amounts in the range of 0.1 microkelvin which are measured by solid state thermometers made of doped silicon.

Of the detectors in HFI twenty of them are unpolarised. They absorb the radiation in an omnidirectional resistance grille that resembles a spiderweb. 32 bolometers are only sensitive to linear polarised light. They absorb the radiation from parallel resistance wires into two grilles that are placed at right-angles to each other, from which each one only senses the polarised components of the electrical field that are parallel to the wires.

The extremely high level of sensitivity of the HFI can only be attained when the whole bolometer and its surrounding area are cooled to temperatures around 0.1 Kelvin. In the test the HFI bolometers displayed a level of sensitivity that is close to the limit that is set in quantum physics for material being absorbed. Planck is the first space experiment in which detectors are cooled to such low temperatures.

In order to achieve this the part of the HFI that lies on the focal plane is designed like a Russian doll (Fig. 16). It consists of increasingly colder layers encased inside each other, each of which protects the next from the radiation and the thermal conduction from warmer construction stages. Each of these layers is cooled by a different machine. This ensures that the last stage can be cooled to 0.1 Kelvin: The shielding system is so effective that the last cooling stage requires a cooling power of less than one microwatt. The temperature of the plate onto which the bolometer is attached must also be very low and very stable as fluctuations in the temperature of the bolometer could be interpreted as real signals from the sky. Highly sensitive thermometers and an original design were developed in order to attain a level of temperature stability that can be expressed in nanokelvin.

As for the LFI, the HFI also uses a modular readout plan in order to attain the necessary stability. The readout electronics of the HFI is based on amplifiers with modulated dark current and low noise that have been specially developed for this project.

No working instrument is similar to the HFI, for which new components, new fundamentals and a completely new architecture were developed. The performance of the HFI as now been tested in the laboratory meets the most optimistic expectations. This also means that the measuring accuracy in space will above all be determined by the amount of information that is contained in the radiation itself.

■ The cooling system

An enormous challenge for Planck was the complex thermal design that is required to operate of the two instruments: The LFI radiometers are optimised for an operating temperature of 20 Kelvin, and the HFI bolometers require even more demanding cooling to 0.1 Kelvin.

Such high cryogenic performance has never before existed in space. It is achieved by PLANCK combining efficient passive cooling with an active three-stage cooling chain. The space probe contains three thermal shields ('V profiles') that separate the warm supply unit at 300 Kelvin from the cold telescope and the instrument bay that are always kept in the dark. Thermal tests on the cryogenic model of Planck have shown that the temperature in the instrument bay will lie under 50 Kelvin. The active chain continues to cool until the extreme values that are required by the detectors are attained. Three different active coolers which work as a single integrated system are used: a hydrogen sorption cooler that supplies 20 Kelvin for the LFI and 18 Kelvin for the HFI, a Joule-Thomson cooler that supplies 4 Kelvin for the HFI and the reference sources of the LFI, and a helium dilution cooler with an open circuit that in a final stage supplies 0.1 Kelvin for the HFI bolometers.

Vibrations in the active coolers represent a possible critical source of unwanted effects.

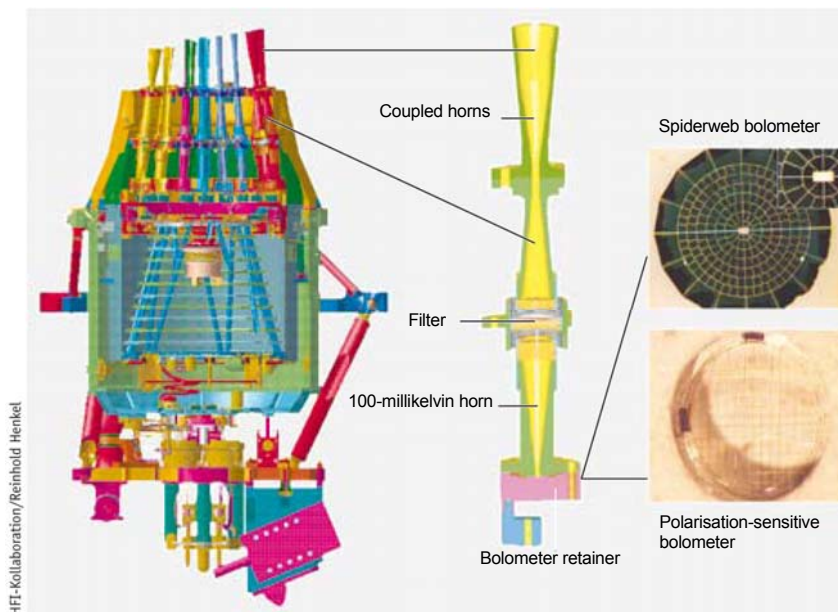
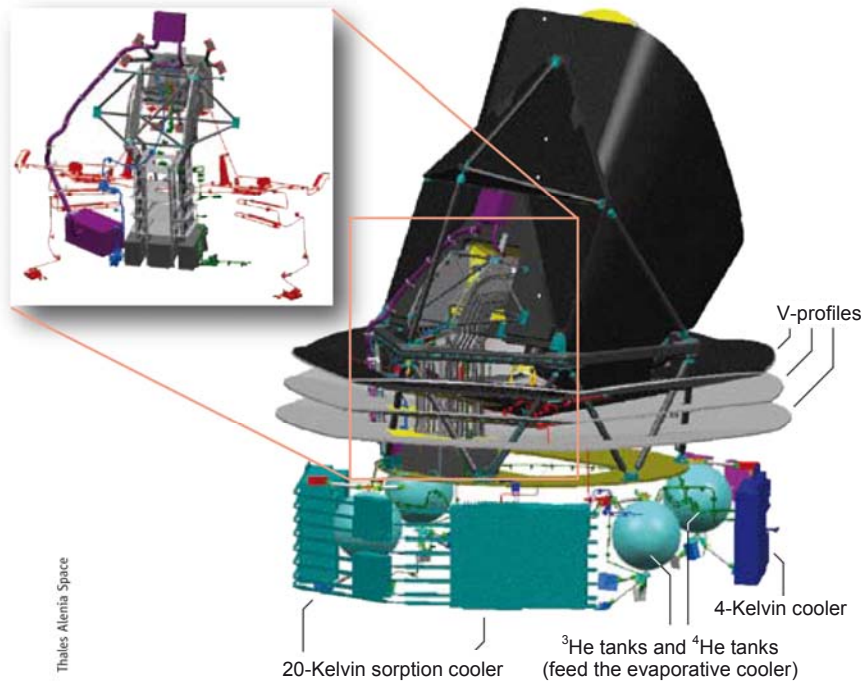


Fig. 16: Left - This sectional view through the cooling system and the detector arrangement for the HFI shows the different thermal components of the 'Russian doll'. Centre - systematic cross-section through a detector unit; the inlet horn antennae that are cooled to 4 K above; the radiation passes through the filters (at 1.6 K) and reaches the bolometer (0.1 K). On the right: a spiderweb bolometer and two polarisation-sensitive bolometers.



▲ Fig. 17: This model shows to what degree the cooling system determines the overall architecture of the satellite. The three V-profiles provide passive cooling to 50 Kelvin: the sorption cooler achieves 18 to 20 Kelvin, and the Joule-Thompson cooler 4 Kelvin. The ^3He and ^4He tanks are used to cool the bolometers to 0.1 Kelvin. The inset shows the lines for transporting the cooling fluids to the focal plane.

For this reason the 18-20 Kelvin stage was achieved by way of a newly designed hydrogen sorption cooler with a closed circuit that does not contain any mechanically moveable parts. The cooler works using a thermal circuit through six compressors that are filled with metal hydride. Depending on its temperature this material absorbs hydrogen or releases it again. The hydrogen is the working fluid in a Joule-Thomson cooler. At any given point in time one of the compressors is warm and releases hydrogen gas at high pressure, one compressor is cooling down, one is heating up, and three are cold and absorbing the gas. An additional sorption bed serves to even out fluctuations in pressure in the low-pressure gas. This mode of operation ensures that no vibrations are passed on to the detector - a unique characteristic of this type of cooler. The 4 Kelvin stage consists of a Joule-Thomson cooler that is powered by mechanical compressors and which is pre-cooled by the sorption cooler to 18 Kelvin.

These compressors are constructed in a "head to head" arrangement that compensates for the pulse. Vibrations are further reduced by way of active electronic compensation of the compressor thrusts. The vibration-free 0.1 Kelvin stage lastly uses a new dilution principle that is based on friction and does not require gravity to operate - only in this way will it be able to be used for applications in space. Achieving not only low temperatures but also their stability is essential for Planck's success. Passive control elements for the damping and active ones for the temperature ensure that the fluctuations in temperature of the various stages do not worsen the internal noise level of the detectors. Some figures illustrate the thermal challenges that the team of instrument developers faced: The space probe's supply unit uses around 1,800 watts, while the detectors are sensitive to 10^{-17} watts (i.e. ten millionths of one watt!) and measure voltages in the region of several nanovolts. Planck's receivers can sense all types of energy: electrical, thermal and mechanical. This means that all types of interfering energy sources must be suppressed by 10^{20} times, which requires an extreme combination of knowledge, experience, creative design, simulations and experimental testing! □

(German version: Matthias Bartmann)
 Interesting weblinks on the Planck mission are available under www.esa.int/education

