THE FIRST DETECTION OF THE CMB THAT OPENED A NEW FIELD IN COSMOLOGY

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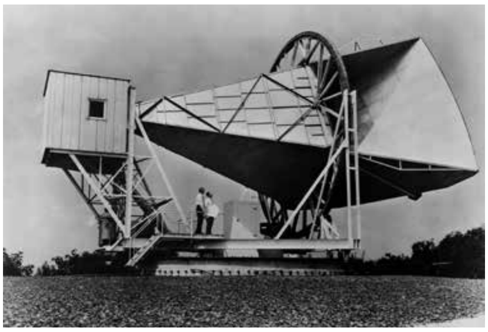

Holmdel antenna used by Penzias and Wilson for the first detection of the CMB emission [credit NASA pictures]

The Cosmic Microwave Background, the oldest signal that can be seen in the sky, is the direct proof that our Universe was extremely dense and hot several billion years ago. The first experimental detection of this fossil radiation has been performed in 1964 and has since then become a powerful tool to probe the formation and evolution of the Universe. Observations of this extremely faint signal pushes the boundaries of many technological developments notably in the fields of optics, detection and cryogenics for space applications.

https://doi.org/10.1051/photon/202211638

THE COSMIC MICROWAVE BACKGROUND AND ITS FIRST DETECTION

Recycling part of a previous experiment in order to perform observations of our Galaxy with an antenna operating at a wavelength of approximatively 7 cm, radio astronomers Arno Penzias and Robert Wilson had to face the presence of a background signal that they could not explain when pointing their antenna in any direction in the sky. After checking for any possible source of noise in their instrument or from the surroundings, as any good scientist would do, this background signal implied an astrophysical emission that they could not interpret immediately. Looking for theoretical explanations, they found out that some other physicists had earlier predicted such an emission, termed the Cosmic Microwave Background (CMB). Some debates exist still about whom first, amongst Alpher and Herman, Friedmann, Lemaître, or Gamov, alongside Robert Dicke who tried to measure such a signal. For this first detection of the CMB, Penzias and Wilson were awarded the 1978 Nobel Prize in Physics.

The farther we probe our Universe in terms of distance, the further we see in time, due to the time that light with finite speed takes to reach the observer. The CMB emission is the most direct evidence of the existence of the so-called **Big Bang**, which happened about 14 billion years ago when the Universe was extremely hot and dense. Immediately after the Big Bang the Universe began cooling down, but for about 380,000 years it was still too hot for charged particles to combine to form neutral atoms. Therefore, during that period, the Universe consisted of a plasma strongly coupled to photons for which the mean free path was small and therefore travelling little distance, resulting in a totally opaque medium in thermal equilibrium. When the temperature dropped below 3000 K, **recombination** of charged particles occurred, forming atoms and leading to matter and radiation decoupling when photons were then free to travel. This transition created the surface of last scattering radiating like a pure blackbody at 3000 K, which is seen nowadays as an isotropic blackbody emission at 2.7 K due to the redshift effect.

THE CMB AS A NEW TOOL FOR OBSERVATIONAL COSMOLOGY

This very faint CMB emission follows Planck's law at T=2.7 K and peaks today at a frequency of about 150 GHz (2 mm wavelength). Any other emission from the sky, from the surroundings, or from the instrument itself (being usually warm) could, and will, be stronger in this region of the electromagnetic spectrum (microwave) than the CMB signal. Cooling down the instrument, and in particular its receiver to reduce noise and therefore gain sensitivity, is required. Penzias and Wilson were able to perform the first detection at a wavelength of 7.35 cm (not even the peak frequency of the CMB) due to the fact that the radio receiver that they were using at the end of their antenna was making use of a switch comparing the signal from the antenna to a termination cooled at a temperature of 4 K, using a tank of liquid helium [1].

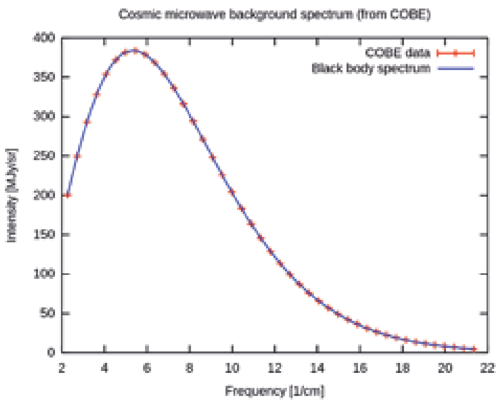


Figure 1. Blackbody spectrum (T=2.725 K) of the CMB as measured by the space mission COBE-FIRAS [2,3]. Crosses are data point with error bars too small to be visible. [Credit from NASA].

A full sky-map of the CMB emission in which the surrounding noise contamination can be mostly removed can only be achieved from a space platform. The second milestone in CMB exploration was achieved in the early 1990's with NASA's COBE satellite [2]. Amongst its outstanding results, leading to the award of the 2006 Nobel Prize in Physics to John C. Mather and George F. Smoot, COBE not only provided the first low-resolution CMB map over the full sky, but realised also the first (and still only) spectroscopic measurement showing a perfect fit to a blackbody emission spectrum (Fig. 1) with a temperature of T= 2.725 ± 0.001 K [3]. To do so, COBE spectrometer was cooled down to 1.6 K using superfluid helium.

Once COBE's sky maps were "cleaned" from instrumental noise and other astrophysical sources, which are seen as contaminants from a CMB perspective, the resulting maps revealed that the CMB temperature was not constant across the sky. Most • • •

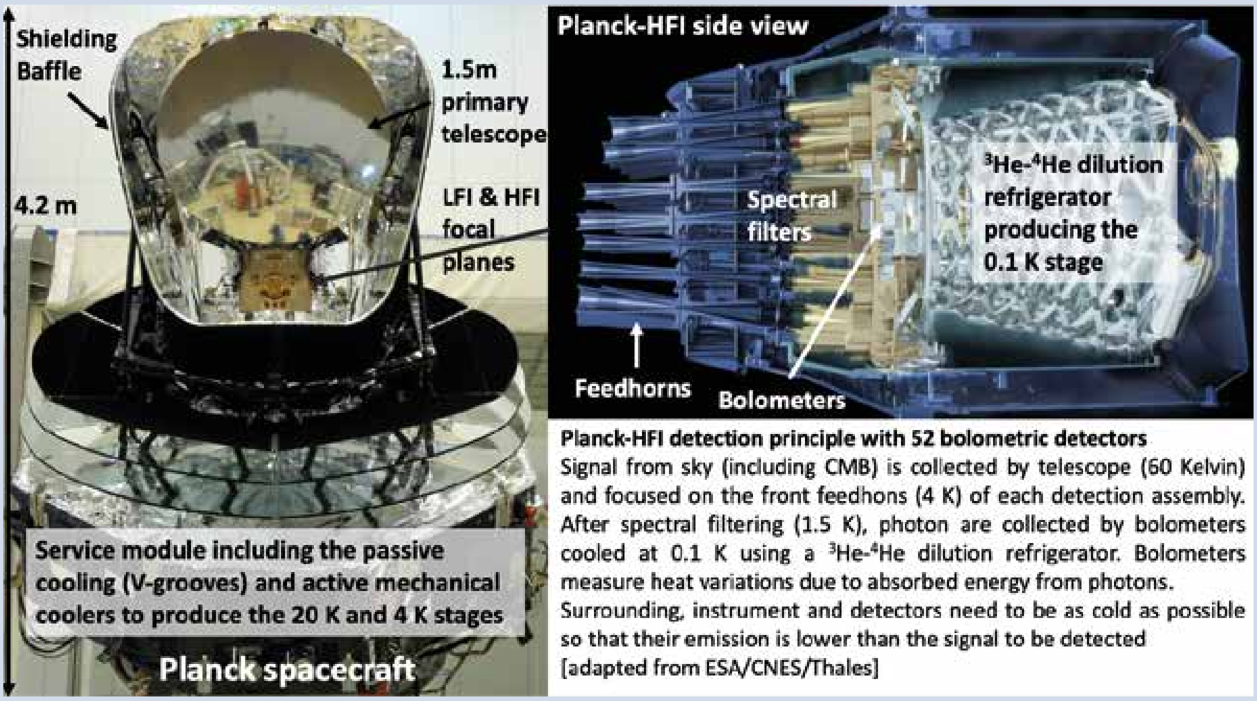
prominently, a temperature variation of ± 0.0035 K was revealed in opposite direction in the sky. This dipole effect is due to a differential redshift (Doppler effect) due to the Galaxy moving with respect to the CMB at a speed of about 600 km/s. Once this effect is removed, we are left with temperature variations that are called anisotropies. Indeed, like a theatre curtain preventing spectators from seeing what is happening backstage, shapes and intensity of movements of this curtain might indicate what is happening beyond it. Similarly, we cannot see past this **surface of last scattering** as the Universe was opaque during that era. However, density inhomogeneities in the primordial plasma, prior to recombination, that then led to the formation of structures (e.g. galaxies, clusters of galaxies) that we now know, have created CMB temperature inhomogeneities across the sky.

This opened a brand-new area of observational and experimental Cosmology, as theory shows that the study of these anisotropies both in intensity and polarisation is a unique tool to probe the formation and evolution of the Universe as well as its geometry and its content through an accurate determination and constraints of the various cosmological constants.

However, to detect these temperature anisotropies with a reasonable signal-to-noise ratio, stringent constraints were put on the instruments to be used. At least an order of magnitude in sensitivity had to be gained with respect to COBE, together with a need for much higher spatial resolution, as COBE's 7-degree resolution was far too coarse to measure the expected spatial variations at angular scales smaller than 1 degree. Accurate control of the instrument is also required in order to reduce some spurious signals (systematic effects). Moreover, with such a faint target signal, any other astrophysical emissions, referred as foregrounds, must also be measured and fitted with high precision in order to be subtracted from the data. This leads to the need of a large spectral range, typically from 30 to 800 GHz.

The balloon-borne project BOOMERanG was the first experiment, after COBE, to measure the CMB anisotropies over a large portion of the sky with sufficient accuracy to perform the first measurement of the temperature anisotropy power spectrum. From these results released in 2000, a crucial conclusion was drawn at that time: the constant setting the curvature of the Universe is equal to 1, and we are therefore living in a flat Universe [4], meaning that our Universe would continue to expand at the same rate as today. However, since then independent measurements with supernovae, have shown that the expansion rate is increasing due to what is called Dark Energy.

Other projects (MAXIMA, DASI, and NASA WMAP space mission) confirmed and improved our knowledge of the CMB with the ESA-led third generation space mission Planck, launched in 2009, being the latest major milestone. The Planck mission [5] consisted of two instruments at the focus of a 1.5 m diameter off-axis telescope. The Low Frequency Instrument (LFI) was using radiometers cooled to 20 K operating between 30 and 70 GHz. The High Frequency Instrument (HFI) used bolometers operating between 90 and 900 GHz, the most sensitive detectors in this frequency range at that time, cooled to 0.1 K (for the first time in space). Together with careful design and calibration of the instruments, in



Planck-HFI detection principle with 52 bolometric detectors
Signal from sky (including CMB) is collected by telescope (60 Kelvin) and focused on the front feedhons (4 K) of each detection assembly. After spectral filtering (1.5 K), photon are collected by bolometers cooled at 0.1 K using a ^3He-^4He dilution refrigerator. Bolometers measure heat variations due to absorbed energy from photons. Surrounding, instrument and detectors need to be as cold as possible so that their emission is lower than the signal to be detected [adapted from ESA/CNES/Thales]

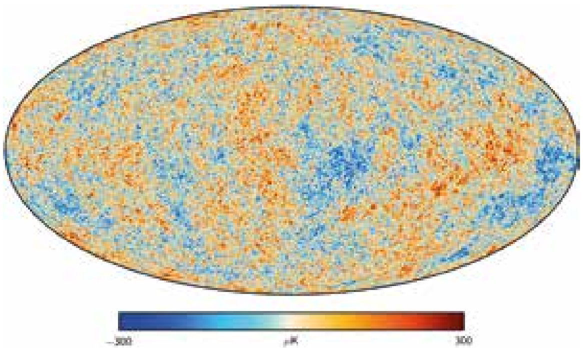


Figure 2. CMB temperature anisotropies sky map reconstructed from the 9 frequency maps measured during the Planck mission lifetime [Credit ESA and the Planck collaboration].

particular the optics for which the telescope beams were measured with a dynamic range better than 80 dB, temperature variation measurements of a few μK per pixel were reached, allowing for a science legacy which has not been surpassed so far [6]. Amongst its many results, notably in the determination of the parameters of the ΛCDM model of our Universe, we can cite that the Hubble constant has been measured as $H_0 = 67.36 \pm 0.54$ km $s^{-1}Mpc^{-1}$ and the age of the Universe is 13.797± 0.023 Gyr. We can also cite the determination of the parameter $n_s = 0.9649 \pm 0.042$, called the spectral index of the initial perturbations, which confirms the existence of an inflationary phase that stretched the tiny quantum fluctuations into the seeds of galaxies and large-scale structures.

TOWARDS THE FUTURE

We have continuously seen that each time major results (some not foreseen) are achieved, cosmologists will have new theories to be proven experimentally. Theory predicts two types of polarisation for the CMB anisotropies: E-modes and B-modes. The Planck mission was not originally designed for extremely accurate measurements of the CMB polarisation, even if its results on the E-mode power spectrum reconstruction are unbeaten still. Measurement of the B-modes, amongst all implications in our understanding of the evolution of the early Universe, will allow for the detection of primordial gravitational waves (before the creation of the CMB) and the phase of inflation (exponential expansion of the Universe just after the Big Bang). However, this measurement would require an increase in sensitivity of about two orders of magnitude with respect to the Planck mission. Planck-HFI bolometers operated at 0.1 K were already photon noise limited (i.e. not limited by the detector sensitivity). Therefore, improvement of the overall sensitivity can only happen through the multiplication of the number of detectors (from a few tens to several thousands) while improving still the performance of each component so that the measurement is not limited by instrument systematics. Needless to say, this represents an incredible technical challenge on which many institutes are working. Several ground-based and balloon projects are being planned and developed, with the new Japan-led LiteBIRD project being potentially the fourth generation CMB space mission. The race is on...

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