Mem. S.A.It. Suppl. Vol. 3, 242

Memorie della
Supplementi

Projects and Progress in CMB Anisotropy Space Cosmology ⋆

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Abstract. With the Wilkinson Microwave Anisotropy Probe (WMAP) a new era for the Cosmic Microwave Background (CMB) observations from the Space has started. The good results obtained by WMAP are to be considered as a solid starting point for all the next CMB experiments. In this framework, the ESA Planck satellite represents the future of the missions designed for space observations of CMB anisotropies, in order to set strong definitive constraints on many cosmological parameters. Only a combined scientific and technological effort will provide the necessary instruments enabling the scientific community to answer all the questions still open.

Key words. Cosmology - Space Missions - Millimeter Wave Astronomy

1. Introduction

The early Universe, starting from an extremely hot and dense condition, cooled with expansion until the temperature dropped below 3000 K, allowing free electrons and protons to form neutral atoms. At this epoch, known as *recombination*, the Universe became transparent: the photons were last scattered off by the electrons and freely propagated, giving rise to the Cosmic Microwave Background (CMB) we observe today like a snapshot of that time. The CMB exhibits a blackbody spectrum with a present temperature of 2.725 K, reached through the cooling due to the slow adiabatic expansion Partridge (1995). The physics of the plasma before the recombination (acoustic oscillations), the physics of the primordial Universe (spectrum of the quantum fluctuations of a scalar field present in the very early Universe, boosted to cosmological scales by the inflation phase Guth (1982)), the expansion and the geometry of the Universe at large scale determined the statistical properties of the CMB temperature and polarization anisotropies. If the distribution of the temperature fluctuations were isotropic and Gaussian (as in the inflationary models, this one confirmed by the recent results of the WMAP space mission Komatsu et al. (2003)), then all the cosmological information present in a CMB sky map can be derived analyzing its angular power spectrum Seljak & Zaldarriaga (1996). The angular CMB

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temperature power spectrum represents a unique resource for a direct investigation of the early Universe and we can use it to determine the cosmological parameters. In standard models, polarization anisotropy is less than 10% and its detection is fundamental to break down the degeneracy in the determination of the cosmological parameters Crittenden et al. (1993): to appreciate it, designing instruments more and more sophisticated and sensitive is a crucial task.

2. Planning CMB Experiments

In planning CMB anisotropy experiments, several important features have to be taken into account: *i*) a good sensitivity and angular resolution (that enable to discriminate between different cosmological models), *ii*) a wide frequency coverage (maximizing the ability to subtract foregrounds contaminating the CMB), and *iii*) minimizing the susceptibility to systematic errors.

Incomplete sky coverage limits the statistical information about the power spectrum coefficients since it increases the sample variance and it smears out features in the power spectrum. Sky coverage is one of the main reason for planning mission from the space, even though full sky coverage satellite missions can be affected by the sample variance too, since highly contaminated parts of the data (such as the Galactic plane) could be discarded. Moreover, space missions also ensure to reach the best accuracy in measures, otherwise limited by the atmospheric emission and by other systematic effects as temperature variations and terrestrial contaminations. A wide frequency coverage significantly improves the accuracy in subtracting the foreground contamination from the primordial CMB anisotropy, providing at the same time a gold-mine of cosmological as well as astrophysical information De Zotti et al. (1999).

Systematic effects, such as main beam distortions, straylight contamination, thermal effects, uncertainty in the pointing direction, calibration errors, and 1/f noise have to be accurately controlled both in the design and operational phase, and reduced in the data analyses.

For all these reasons, although deep CMB measurements can also be obtained with relatively cheap long duration balloon experiments, the Space represents the best available laboratory.

3. Measuring the CMB: past and present experiments

The first detection of the intrinsic anisotropies at angular scales of about 10° and at a level of $\Delta T/T \simeq 10^{-5}$ in the temperature of the CMB occurred in 1992 by the Differential Microwave Radiometer (DMR) onboard the COsmic Background Explorer (COBE) satellite Smoot et al. (1992).

Before COBE, the only temperature anisotropy detected in the CMB was of dipole nature Smoot et al. (1977). This component is the largest anisotropy present in the CMB (3.372 ± 0.007 mK) and it is due to a Doppler shift originated by the motion of the observer with respect to the rest frame of the CMB.

After COBE, the goal of CMB experiments has been to increase the angular resolution of the maps to study the small scale features in the angular power spectrum. During the last years, many experiments have been dedicated to measure the degree and sub-degree angular scale structures of the CMB temperature across relatively large patches of sky with a high signal-to-noise ratio Bersanelli et al. (2003).

Two balloon borne experiments, BOOMERanG de Bernardis et al. (2001) and Maxima Lee et al. (2001), were able to reconstruct the first two peaks of the power spectrum with an excellent agreement, for frequencies higher than 90 GHz. BOOMERanG is a microwave telescope with sensitive cryogenic detectors cooled at 0.3 K, that flew the first time in 1998, above Antarctica. BOOMERanG measured at four different wavelengths

(90, 150, 240, and 410 GHz) the angular distribution of the CMB on $\simeq 3\%$ of the sky, with a resolution of about $10'$ and a sensitivity of about 20 μK per pixel. Its main result was the measurement of the large scale curvature of the Universe, constraining the density parameter Ω to be $0.85 < \Omega < 1.1$ (95% confidence interval).

Since 1998 the focal plane of the instrument has been completely redesigned in the new B2K, to study the polarization as well as the temperature anisotropy of the CMB. B2K has been launched on January 2003. The mission was not completed because of problems occurred during the flight; anyway the partial data taken, currently under reduction, seem to be promising.

At lower frequencies, the Degree Angular Scale Interferometer, DASI Kovac et al. (2002), is a 13-element interferometer designed to measure temperature and polarization anisotropy of the CMB over $1.3 \div 0.2$ degrees operating between $26 \div 36$ GHz.

The Wilkinson Microwave Anisotropy Probe (WMAP) mission, designed by NASA, is the most advanced cosmological observatory measuring the CMB anisotropies in the Lagragian point L2 of the Sun–Earth system Bennett et al. (2003) at a distance of 1.5×10^6 km from the Earth. The instrument observes the temperature difference between two directions (as did COBE) using two nearly identical sets of optics. The WMAP optical system consists of two back-to-back shaped offset Gregorian telescopes, that focus radiation into twelve corrugated horns that feed pseudo-correlation differential radiometers with High Electron Mobility Transistor (HEMT) amplifiers passively cooled to $\simeq$ 90 K.

WMAP is producing full sky maps in five frequency bands (K, K_α, Q, V, and W) from the radiometer data of temperature differences measured over the full sky. The main beam angular resolutions are $49.2'$, $37.2'$, $29.4'$, $19.8'$, and $12.6'$ at 23, 33, 41, 61, 94 GHz respectively. WMAP presented the results of the first year sky survey in February 2003. It evaluated all the cosmological parameters with unprecedented accuracy Spergel et al. (2003). The results strengthen the constraints previously set by other CMB experiments on cosmological models providing a value for the total mass-energy of the universe close to 1 ($\Omega = 1.02 \pm 0.02$): it implies that our Universe is about flat. A new remarkable result concerns the estimate of the reionization age, starting from constraints imposed by measures on the optical depth: $\tau \simeq 0.17 \pm 0.04$ implies a reionization epoch of $t_r = 180^{+220}_{-80}$ MYr after the Big Bang corresponding to a redshift $z = 20^{+10}_{-9}$ for a range of ionization scenarios. This early reionization is incompatible with the presence of a significant warm dark matter density Bennett et al. (2003).

By combining the WMAP data with other finer scale CMB experiments (ACBAR and CBI), 2dFGRS measurements, Lyman α forest data, and SN1a, a best fit of the cosmological parameters was found, allowing to estimate also the age of the Universe as $13,7 \pm 0,2$ GYr. The good results obtained by WMAP in the first year of its mission, to be further refined in the next three years mission, are to be considered as a solid starting point for all the next CMB experiments.

4. The future: the Planck satellite

Planck represents the third generation of mm-wave instruments designed for space observations of CMB anisotropies within the new Cosmic Vision 2020 ESA Science Programme. Planck will be launched in 2007 and will carry the state-of-the-art of microwave radiometers (Low Frequency Instrument, Mandolesi et al. (1998)) and bolometers (High Frequency Instrument, Puget et al. (1998)), operating between 30 and 900 GHz in nine frequency channels, coupled with a 1.5 m telescope.

The Low Frequency Instrument is a system of 22 wide band radio receivers covering the frequency range $30 \div 70$ GHz: they employ very low noise ampli-

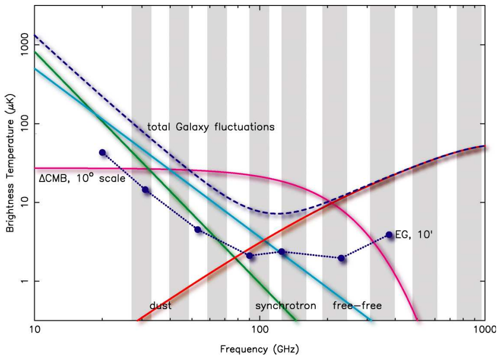

Fig. 1. Frequency dependence and approximate relative strength of Galactic synchrotron, free-free, and dust emission compared with that of the cosmic microwave background and its features. In the first mission year WMAP has found that the minimum is sensibly displaced at about 60 GHz.

fiers based on Indium Phosphide HEMTs (High Electron Mobility Transistors). The radiometers were designed in order to reduce the 1/f noise induced by gain and noise temperature fluctuations in the amplifiers Seiffert et al. (2002). A differential pseudo-correlation scheme was chosen: the power coming from the sky is received by 12 profiled-corrugated feed horns and continuously compared with a reference black body signal (provided by a reference load thermally linked to the HFI 4K stage) at a temperature as close as possible to the sky temperature. The LFI focal plane unit is actively cooled at 20 K by a vibrationless sorption cooler that represents the last frontier in the space cryogenic technology.

The High Frequency Instrument covers the high frequency range with 48 bolometric detectors, operating at a nominal temperature of 0.1 K, divided into six frequency channels (100, 143, 217, 353, 545, and 857 GHz). Together with the high sensitivity Spider-Web bolometers, in three frequency channels the last generation PSB (Polarization Sensitive Bolometers) will be used. In order to optimally exploit the performances of the detectors, HFI is provided with two cooling systems: a Dilution Cooler Subsystem (0.1 K) and a 4K Cooler (4 K).

Main characteristics of both the instruments are summarized in Tab. 1.

The Telescope is a Gregorian off axis, composed of two mirrors (1.9 × 1.5 m the primary and about 1 m the diameter of the secondary) both having an ellipsoidal shape Villa et al. (2002). The conical constants, the focal length, the tilting of the mirrors were combined to reduce the main beam aberrations, the curvature of the focal surface, and the spillover as well.

The main scientific tasks of Planck are: *i*) to make full sky maps of the temperature CMB anisotropies, with an angular resolution lower than $10'$ and an accuracy fixed only by astrophysical limits, *ii*) characterize the state of CMB polarization (LFI is intrinsically sensitive to the polarization in all its channels, HFI has three channels dedicated to its investigation), *ii*) produce full sky maps for the most important Galactic and extragalactic sources, *iv*) provide a detailed analysis of important astrophysical phenomena (Sunyaev & Zel'dovich, Integrated Sachs Wolf, Weak Lensing, etc).

Because of its extremely larger coverage of the frequency spectrum, of its optimal angular resolution ($5'$ with its high frequency channels compared to the $14'$ typical of the 94 GHz channel of WMAP), of its sensitivity (ranging from three to ten times better than WMAP), and of a corresponding unprecedented accuracy in controlling the systematic effects, Planck will answer to many questions left unsolved by WMAP and will set a fixed point in the analysis of CMB anisotropies.

The reconstruction of the CMB angular power spectrum at small angular scales is considered a task of primary importance: WMAP has directly investigated the power spectrum until the multipole $\ell \simeq 800$, pushing beyond only by combining data coming from other CMB experiments as ACBAR and CBI. Planck will trace the power spectrum until $\ell \simeq 2000$ and will also accu-

Table 1. LFI and HFI receiver characteristics and expected performances.

	LFI			HFI					
Central Frequency (GHz)	30	44	70	100	143	217	353	545	857
Beam Size (arcmin)	33.0	23.0	13.0	9.2	7.1	5.0	5.0	5.0	5.0
Number of Detectors	4	6	12	4	12	12	12	4	4
Sensitive to Linear Pol.	yes	yes	yes	no	yes	yes	yes	no	no
Average $\Delta T/T_{therm}$ (μK/K)	2.2	2.8	4.9	2.2	2.4	3.8	15.0	80.0	8000.0

rately investigate the behavior at very low ℓ's.

Different combinations of the cosmological parameters may produce temperature angular power spectra not distinguishable: the degeneration can be broken by means of polarization measures, distinguishing between adiabatic and isocurvature fluctuations. Moreover, studying the rotational modes of the polarized field may help to understand the formation of gravitational waves during the inflation allowing us to estimate its energetic scale.

Planck will precisely determine the ET and E components of the polarized power spectrum and has a good chance to measure also the B component induced by initial tensorial perturbation producing gravitational waves and by the lensing.

Foregrounds, matching maps at different frequencies, will be evaluated with high accuracy by means of a perfect mix of high sensitivity and angular resolution, together with wide spectral coverage. This study will allow to find traces of non-Gaussianities in the CMB as a test to discriminate among various cosmological models. The detection of the Sunyaev-Zel'dovich (SZ) effect Sunyaev & Zel'dovich (1972) in a large number of clusters, combined with X-ray observations, will lead to an independent measurement of the Hubble constant Cavaliere et al. (1977). Mooreover, this detection will enhance knowledge of the population of clusters and of the properties of their hot gas.

5. Open questions in Cosmology

The next future will promise to answer also to other unresolved problems: what is the Dark Matter made of? what is the Dark Energy made of? what is the potential of the Inflaton?

Inflation is a possible scenario; however, other alternative evolutionary theories already exist: for example, the giant brane collision model, also known as the Ekpyrotic Universe (an intriguing model starting out with a cold, static five-dimensional spacetime close to being perfectly supersymmetric, Khoury et al. (2002)) or the Generalized Chaplygin Gas model (GCG) (a perfect fluid with negative pressure, a possible way to explain the accelerated expansion of the Universe unifying Dark Energy and Dark Matter Carturan & Finelli (2002)).

A lot of cosmological parameters, depending on the cosmological model, are still free. The evolutionary framework of the physical constants, with particular regard to the fine structure constant, have to be lined. Next CMB experiments, and among this Planck, will be deputed to set stronger constraints on it.

6. Conclusions

During its brief history, CMB science has contributed to understand many aspects of cosmology and astrophysics; at the same time, this increased knowledge has opened a lot of questions concerning the history and the structure of our Universe. With the beginning of this millenium a new era in the study of the Universe has started, named *precision cosmology.* The next CMB

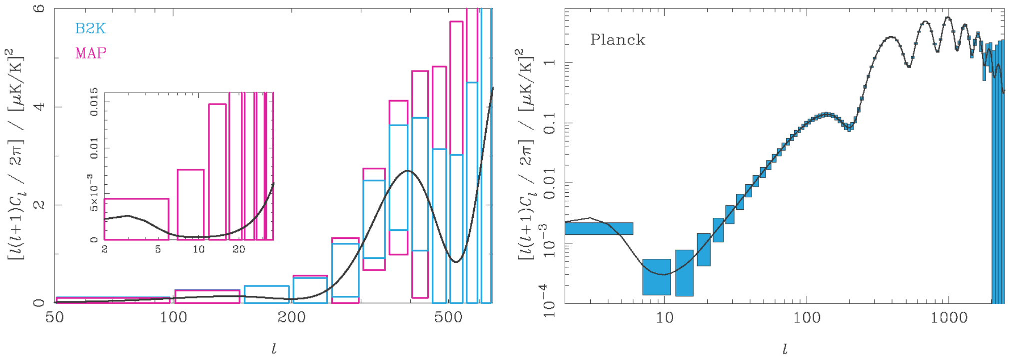

Fig. 2. Comparison (error bars are displayed) between polarization power spectra measured by B2K and WMAP (*left panel*)and simulated for PLANCK (*right panel*).

experiments, like PLANCK, will be adequate to clear a lot of open questions. To make this, scientific research has to walk tight together with the technologic improvement. In fact, high instrumental sensitivities and a high control of systematics, sometimes beyond the actual capabilities, are required to reach the ambitious goals lined in this paper, and only by combining the efforts of the whole scientific community this precious mine of information, that the CMB represents, will reveal us its numerous secrets.

Acknowledgements. We gratefully acknowledge C. Burigana and F. Finelli for the helpful clarifying discussions.

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