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CMB and precision cosmology: status and prospects

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Abstract. The study of the cosmic microwave background (CMB) has played a crucial role in establishing a new standard of precision in the determination of cosmological parameters. The full-sky, high-resolution maps of the CMB recently produced by the WMAP space mission have reinforced the evidence in favor of a flat universe, dominated by dark matter and dark energy, and consistent with the predictions of the inflationary scenario. Further high-precision observations of the CMB, such as those that will be carried on by ESA's Planck Surveyor, will further strengthen our knowledge of the Universe.

Key words. Cosmic microwave background — Cosmology: observations — Cosmology: theory

1. Introduction

The cosmic microwave background (CMB) is a powerful tool to investigate the physics of the early Universe and to constrain the parameters of the standard cosmological model. It provides a picture of the Universe when it was only a few hundred thousand years old, at the time when neutral atoms formed and photons decoupled from the matter. The fact that the COBE satellite found the CMB to have a black body spectrum to an astonishing precision (Fixsen et al. 1996) is a clear signature of an early period of matter-radiation equilibrium and a major triumph for the big bang model.

Since the distribution of the CMB photons reflects that of matter at the time of decoupling, any inhomogeneities in the matter density (needed to seed structure formation in the Universe by gravitational instability) must leave an imprint as fluctuations of the CMB temperature. CMB temperature anisotropy was first detected by COBE in the early 90's (Smoot et al. 1992). The fact that the level of anisotropy is very small (about a part in one thousand, corresponding to temperature fluctuations of some tens of μK) simplifies the task of making theoretical prediction of the anisotropy pattern, since linear perturbation theory can be applied.

Most cosmological information encoded in the anisotropy pattern is concentrated at angular scales smaller than about 1 degree on the sky, corresponding to perturbations that were inside the horizon (i.e. in causal contact) before decoupling. On these scales, physical processes in the early Universe were able to leave

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their imprint on the CMB. The main CMB observable is the angular power spectrum of temperature anisotropy, C_l (see Figure 1). Since each l is related to an angular scale θ on the sky given approximately by $l \sim 180°/\theta$, the power spectrum at high l's probes sub-horizon angular scales at the time of decoupling and carries the imprint of physical processes which occurred in the early Universe. Conversely, low l's basically probe initial conditions in the early Universe (although secondary processes may alter the CMB photon distribution after decoupling).

The detailed shape of the CMB power spectrum is strongly dependent on cosmological parameters. For example, given an initial distribution of density perturbations in the early Universe, the relative height of the peaks in C_l represents a good indicator of the density of baryonic matter in the Universe. On the other hand, the position of the peaks depends on the way the physical scale of sound horizon at decoupling is mapped into an angular dimension on the sky. This mainly depends on the geometry of the Universe: for example, in an open Universe, a certain physical scale at decoupling is seen today under a smaller angle than in a flat Universe. So, the position of the peaks in the CMB angular power spectrum is a good indicator of the total density of the Universe.

In the decade following the release of the COBE results, the experimental efforts focused on measuring the CMB anisotropy at intermediate and small angular scales, that were not accessible to COBE because of its low angular resolution. Several experiments, conducted from 1992 to 1998, either from the ground or from balloon-borne payloads, explored the CMB angular power spectrum in the region between few arcminutes to about one degree. Although each single experiment could only probe a narrow band in l-space, the combined measurements seemed to indicate a rise in the power spectrum at $l \sim 200$.

Thanks to the progress in detector technology, between 1998 and 2000 the experiments TOCO (Miller et al. 1999), BOOMERanG (de Bernardis et al. 2000) and MAXIMA (Hanany et al. 2000) were able independently, for the first time, to clearly resolve the first acoustic peak in the angular power spectrum. BOOMERanG and MAXIMA also produced the first high-resolution (about 10 arcminutes) maps of the CMB, although on small patches of the sky. The detection of the first peak served to support the inflationary scenario, and allowed to measure the total energy density of the universe with unprecedented accuracy. This turned out to be very close to the critical value, $\Omega \simeq 1$, corresponding to a flat universe (Balbi et al. 2000; de Bernardis et al. 2000).

Later, in 2001, the DASI (Halverson et al. 2002), BOOMERanG (de Bernardis et al. 2002) and VSA (Grainge et al. 2003) experiments detected hints of a second acoustic peak in the CMB power spectrum, further strengthening the case for the adiabatic nature of primordial fluctuations. Then, in 2002, the Archeops (Benoit et al. 2003) experiments secured the measurement of the first acoustic peak, and the CBI (Pearson et al. 2003) and ACBAR (Kuo et al. 2002) experiments explored the spectrum at smaller angular scales, measuring the expected damping of primary anisotropy.

2. The WMAP satellite

The WMAP (Wilkinson Microwave Anisotropy Probe) satellite[1], launched by NASA aboard a Delta rocket on June 30, 2001, represents the state of the art of CMB experiments. In many ways, WMAP is a follow-up to COBE. It was designed to make full-sky map of CMB anisotropy by looking at temperature differences in the sky, using differential radiometers in five frequency bands. WMAP scans large regions of the sky in relatively short times, with a strong cross-linking among observations performed at different times: this is very useful to control systematic effects and correlated instrumental noise. WMAP operates from the L2 Lagrangian point, completing a full sky coverage in a six month period. WMAP detector technology is based on HEMT (High Electron Mobility Transistor) radiometers, passively cooled at about 90 K.

[1] http://map.gsfc.nasa.gov

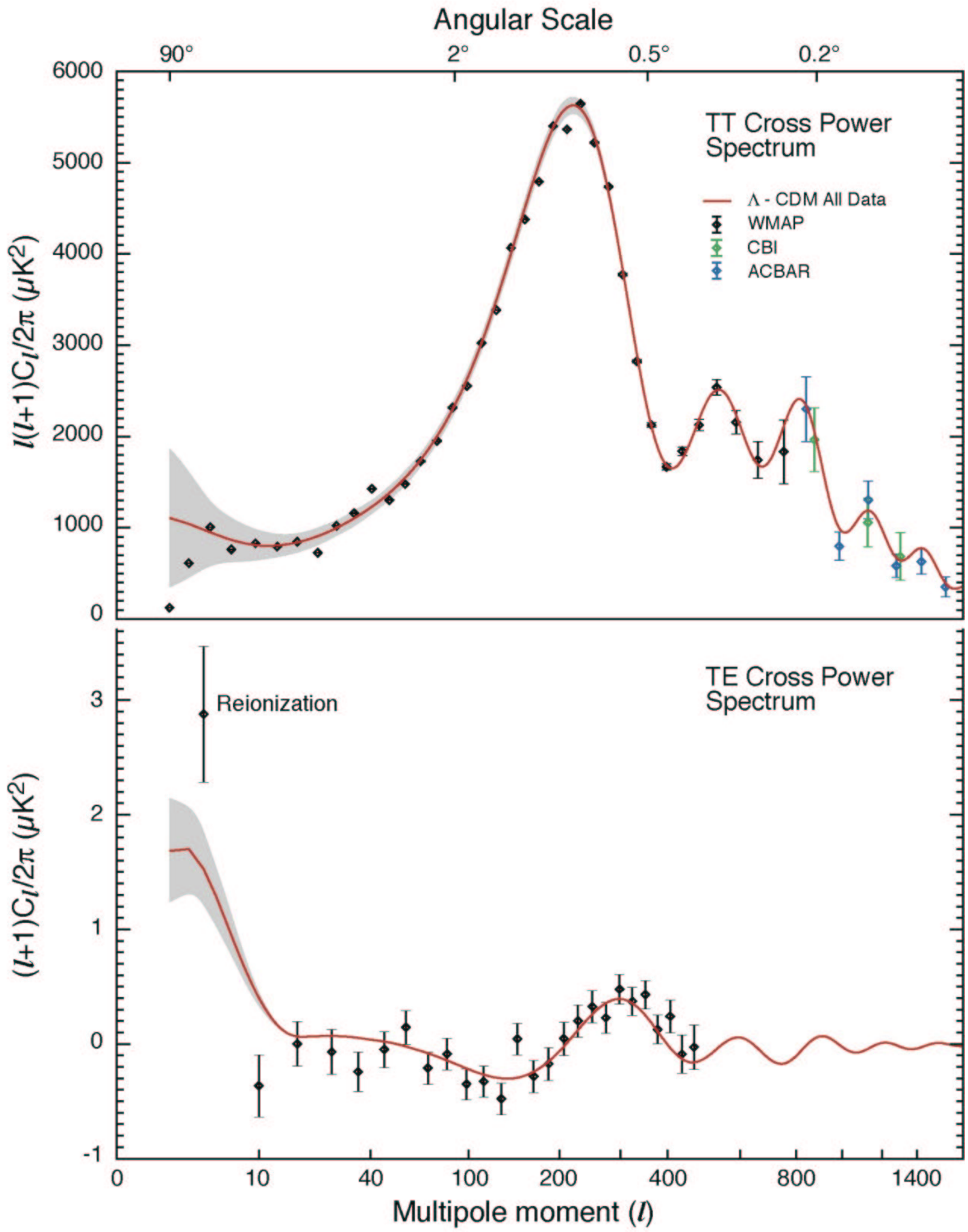

Fig. 1. The CMB angular power spectrum. *(Top)*: the temperature power spectrum. The dots are the measurements from the WMAP (Bennett et al. 2003), ACBAR (Kuo et al. 2002) and CBI (Pearson et al. 2003) experiments. The continuous line is the theoretical model which best fits the data. The grey region represents the cosmic variance uncertainty for this theoretical model. *(Bottom)*: the temperature-polarization correlation power spectrum. Note that this is not multiplied by the usual factor of l. (From Bennett et al. 2003)

Table 1. Some cosmological parameters estimated by WMAP (from Bennett et al. (2003))

Parameter	Symbol	Value
Total density	Ω	1.02 ± 0.02
Baryon density	Ω_b	0.044 ± 0.004
Dark matter density	Ω_m	0.27 ± 0.04
Dark energy density	Ω_Λ	0.73 ± 0.04
Equation of state of dark energy	w	< -0.78 (95% C.L.)
Hubble constant (km s^{-1} Mpc^{-1})	H_0	71^{+4}_{-3}
Age of the Universe (Gy)	t_0	13.7 ± 0.2
Optical depth of the Universe	τ	0.17 ± 0.04
Spectral index of primordial density perturbations	n_s	0.93 ± 0.03

Results of the first year of observations by WMAP (August 2001-August 2002), corresponding to two full-sky surveys, were announced at the beginning of 2003 (see Bennett et al. (2003) and companion papers cited therein). Data collected later are currently being analyzed. The pattern of anisotropy seen in the WMAP maps is consistent with that observed by COBE after four years of observation. WMAP has 30 times better resolution than COBE. When the WMAP map is degraded at COBE resolution, the difference map is below the instrumental noise level.

Figure 1 shows the CMB temperature anisotropy power spectrum measured by WMAP. This is the best currently available measurement of the power spectrum and is cosmic variance limited up to $l \simeq 350$. WMAP results provide an extraordinary confirmation of the theoretical predictions. The presence of at least two acoustic peaks in the power spectrum is evident. The cosmological interpretation of these results lends further support to the standard cosmological model based on big bang plus inflation. A flat universe, with adiabatic, gaussian, scale-invariant primordial density fluctuations is perfectly consistent with the WMAP data. The values of the main cosmological parameters, estimated using the WMAP data, are summarized in Table 1. These values are generally more precise than those obtained with other kinds of observations, and are consistent with them. For example, the baryon density at recombination measured by WMAP is in agreement with big bang nucleosynthesis predictions and measurements of the primordial abundance of light elements (O'Meara et al. 2001; Pettini & Bowen 2001; D'Odorico et al. 2001); the Hubble constant value agrees with the measurement by the Hubble Space Telescope (Freedman et al. 2001); the age of the Universe is consistent with the value from stellar observables (Reid 1997; Hansen et al. 2002); finally, the dark matter content of the Universe is in agreement with the one derived by the large-scale matter distribution (Verde et al. 2002). The low value of the matter density, combined with the fact that $\Omega \simeq 1$, confirms that most of the energy density in the Universe is provided by dark energy, as recently indicated by high-redshift type Ia supernovae observations (Perlmutter et al. 1999; Riess et al. 2001). When combined with other astronomical data (high-redshift type Ia supernovae and the matter distribution inferred from redshift surveys) WMAP observations are able to constrain the equation of state of the dark energy component (see Table 1). The outstanding concordance among completely different kinds of observations testifies the level of maturity reached by cosmology in recent times.

A fraction of the CMB signal is predicted to be linearly polarized. Although the polarized component is expected to be small (about 10% of the total signal) it carries valuable cosmological information. A first detection of CMB polarization, in agreement with theoretical predictions, has been announced by the interferometric experiment DASI (Kovac et al. 2002). WMAP detected a correlation between CMB temperature anisotropy and polarization, as expected theoretically (Kogut et al. 2003). This allowed to set limits on the reionization history of the Universe. The integrated optical depth to reionization measured by WMAP is $\tau = 0.17 \pm 0.04$. For a range of plausible models, this corresponds to a reionization at redshift $z_r = 20^{+10}_{-9}$ (95% C.L.) or an epoch $t_r = 180^{+220}_{-80}$ Myr (95% C.L.) after the big bang. Two features of the temperature-polarization correlation measured by WMAP gave further support to the inflationary scenario and to adiabatic primordial density perturbations: the presence of an antipeak at $l \simeq 130$, corresponding to scales that were outside the horizon at decoupling, and the presence of a peak at $l \simeq 300$ that is out of phase with the first peak in the temperature power spectrum (see Fig. 1).

WMAP mission has been approved for 4 years of operation in L2. In the next few years, further data and analysis will provide more and more detailed cosmological information.

3. The Planck Surveyor

Despite its extraordinary achievements, the WMAP mission does not represent the end of the story. Much remains to be told about the CMB temperature anisotropy. On one hand, WMAP angular resolution does not allow to investigate the damping tail of the CMB power spectrum: although the first two acoustic peaks in the spectrum are now accurately resolved, higher l's are affected by large uncertainties. Other experiments, especially interferometers, are starting to unveil the small angular scale details of the anisotropy pattern, but much work needs to be done. On the other hand, WMAP maps are still affected by a non negligible instrumental noise, which strongly reduces the possibility of direct pixel space analyses.

ESA's Planck Surveyor[2], planned for launch in 2007, will represent the third-generation CMB space mission. The main product of the Planck mission will be full-sky maps in 9 frequency bands between 30 and 900 GHz. Planck frequency coverage will be the widest ever for a single microwave experiment. This is crucial to separate the various components that constitute the observed signal, and will allow the investigation of a large variety of poorly known astrophysical processes, both galactic and extragalactic. Planck will carry on board two different instruments: the HFI (High Frequency Instrument), based on bolometric detectors, and the LFI (Low Frequency Instrument), which uses HEMT radiometers. Exploiting this redundancy and comparison among measurements will be extremely important for the detection and removal of systematics.

Planck's instrumental sensitivity will be several times better than WMAP's. The design of Planck's detectors and optics (a 1.5 m primary mirror and a off-axis secondary, coupled to an array of corrugated horns in the focal plane) will allow to obtain the best possible resolution at each frequency, making it possible to resolve details of a few arcminutes in the sky.

The accuracy of the CMB angular power spectrum measurement by Planck will be limited by cosmic variance and by unavoidable foreground contamination, over the entire range of angular scales relevant to the primary CMB anisotropy, i.e. from $l = 2$ up to $l \sim 1000$, well below the damping scale. This will allow to fully extract the vast amount of cosmological information encoded in the CMB. Planck will be able to measure the cosmological parameters to unprecedented accuracy, minimizing the need of external input from other observations.

The full-sky maps produced by Planck will have a signal-to-noise ratio much larger than 1: this means that Planck's maps will be real pictures of the Universe at recombination. This will allow to accurately investigate physical processes which affect the CMB statistics beyond the angular power spectrum, such as small deviations from gaussianity of the primordial fluctuations, predicted in some theoretical scenarios.

Planck will be the definitive mission for the investigation of CMB temperature anisotropy. On the other hand, Planck detectors were also designed to be sensitive to the polarized component of the CMB signal, although not explicitly optimized for this measurement. This will

[2] http://astro.estec.esa.nl/Planck

allow Planck to say something relevant on the new frontier of CMB investigation.

4. Conclusions

Cosmology has developed into a fully mature science. The parameters of the big bang model are now known with great accuracy, and the constraints are expected to get tighter in the future. Inflation has not been falsified, and its main predictions are strikingly consistent with observations. The results obtained using completely different cosmological probes are in remarkable agreement among themselves, as well as with theoretical predictions. Nonetheless, many fundamental questions are still open (see, e.g., Peebles 2003). The pace of experimental and theoretical progress, however, does not seem to be close to a halt.

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