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CMB cosmology: current status and experimental trends

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Abstract. Several ground, balloon and space based experiments have recently provided detailed maps of the Cosmic Microwave Background. We review the status of the observations and their implications for the current cosmological model. Then we focus on unresolved issues and on the research still to be done to really achieve concordance cosmology, with particular attention to what can be done from Antarctica.

Key words. Cosmology, Cosmic Microwave Background, Antarctic Astronomy

1. Introduction

Our current understanding of the cosmological evolution of the universe is heavily based on measurements of the Cosmic Microwave Background. This observational evidence has been accumulated in the last 15 years. In 1992 COBE-FIRAS measures the spectrum of the CMB with incredible precision (Mather et al., 1994). The thermal spectrum at 2.735K and the high photons to baryons ratio, together with the measured primordial abundances of light elements is evidence for a hot initial phase of the Universe, which had been predicted about 50 years before (Gamow, 1946). Meanwhile COBE-DMR detects the small (10ppm) large-scale anisotropy of the CMB (Smoot et al., 1992). This incredible smoothness is not explained in the naive Hot Big Bang theory, and calls for an inflationary process happening in the first split second after the Big Bang (Kolb and Turner, 1990). In year 2000 BOOMERanG and MAXIMA map the temperature fluctuations of the CMB at sub-horizon scales ($\lesssim 1^o$). The signal is detected well above the noise, and has the correct frequency spectrum (de Bernardis et al., 2000). The angular power spectrum of the detected signal features multiple peaks, at multipoles $\sim$ 210, 540 and 830 (Netterfield et al. (2002),de Bernardis et al. (2002)). The simplest interpretation is that this is the result of acoustic oscillations in the primeval plasma (Peebles et al. (1970), Sunyaev & Zeldovich (1970)). The location of the first peak implies that the typical angular size subtended by the acoustic horizon at recombination is $\sim 1^o$, which in turn means that the geometry of the universe is flat ($\Omega = 1$, as predicted by inflation). The amplitude and location of the first, second and third peaks allows to estimate $\Omega_b = 0.02$, in agreement with big bang nucleosynthe-

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sis, and the slope of the power spectrum of the CMB anisotropy $n_s \sim 1$ (Netterfield et al. (2002),Ruhl et al. (2003)). This is in agreement with the expectation of the basic inflationary model. Consistent results are obtained by several independent experiments (Miller et al. (1999), Torbet et al. (1999), Mauskopf et al. (2000), Hanany et al. (2000), Leitch et al. (2001), Scott et al. (2002), Mason et al. (2002), Benoit et al. (2003 a), Benoit et al. (2003 b), Kuo et al. (2002)). Early this year the results from the first year of operation of the WMAP satellite have been published ((Bennett et al, 2003), Kogut et al. (2003)). These data are calibrated to better than 1% and cover the full sky. The $< TT >$ power spectrum is limited by cosmic variance up to $\ell \sim 350$. The first two peaks and dips are measured with very high accuracy. The power spectrum of $< TE >$ (correlation between anisotropy and E-modes of the polarization) is in agreement with the acoustic oscillations scenario. An excess at low ℓ is the signature of reionization. These data represent a beautiful, firm confirmation of all we knew about the CMB, and pose new questions. In fig.1 we compare the power spectra of CMB anisotropy measured by WMAP and by BOOMERanG, and plot the polarization power spectra measured by WMAP and by DASI. The agreement of these datasets with the adiabatic inflationary model is stunning. When a bayesian analysis of CMB data alone is used to constrain the cosmological parameters, the following results are found, and are stable when other cosmological observations are added: the flatness of the Universe, the fact that fluctuations are nearly scale invariant, gaussian and adiabatic, the density of baryons. Since the interpretation of these results is based on well understood physics, these are considered solid achievements of cosmology.

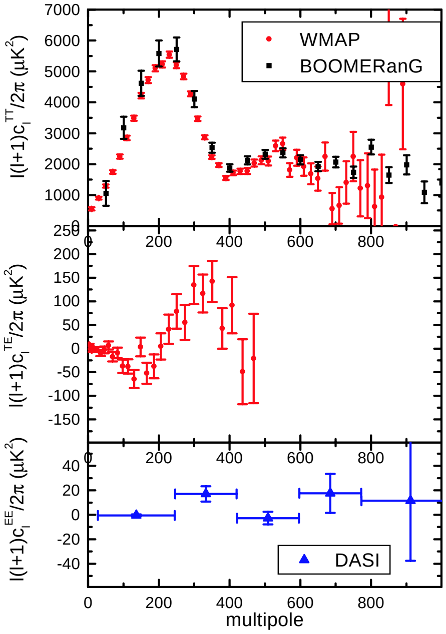

Fig. 1. CMB anisotropy and polarization data ($< TT >$, $< TE >$, $< EE >$ power spectra) from BOOMERanG, DASI and WMAP.

2. CMB cosmology after WMAP

There are, however, outstanding open issues in CMB cosmology. The first two points in the following could rather be considered open issues for the standard model of particle physics, but the border between the two sciences is very fuzzy nowadays.

- We know that $\sim 25\%$ of the Universe is made of Dark Matter, but we do not know what that is. This is a long standing issue, dating back to Zwicky (1933). Modern direct searches for dark matter candidates have not converged towards a satisfactory solution yet, and the indirect evidence we have does not constrain significantly the parameters space of the candidates (Olive, 2003).
- We know that $\sim 70\%$ of the Universe is made of Dark Energy, but we have no idea of what that is. Moreover, all attempts to measure the equation state (i.e. w, the ratio

between pressure and energy density) point towards a cosmological constant ($w \sim -1$) and slightly disfavor quintessence models ($w > -1$) (Spergel et al, 2003), which would be more appealing from the physical point of view.

- Flatness, Scale Invariance, Gaussianity, the anticorrelation between temperature and polarization at large scales are all consistent with the Inflation hypothesis (Kolb and Turner, 1990). However, particle physics does not have an univocal physical description of the inflaton field responsible for inflation.
- At large angular scales the CMB anisotropy measured by COBE and WMAP is significantly less than what is expected in the current ΛCDM scenario, fitting so well the remaining multipoles range (Spergel et al, 2003).
- When WMAP data are combined with other cosmological evidence, the best fit spectral index drops to $n_s = 0.93 \pm 0.03$, and there is 2σ evidence for a change of the spectral index: $dn_s/d\ln k = -0.031 \pm 0.017$ (Bennett et al, 2003).
- The WMAP data suggest reionization earlier than expected: $\tau_r = (0.17 \pm 0.04)$ i.e. $z_r = 20 \pm 10$ at 95% CL. This means, at the very least, that reionization is not a simple process: it could have happened in bursts, or with other complex sequences of events.
- There is excess power with respect to the ΛCDM model in the power spectrum of the microwave sky at large multipoles ($\ell \gtrsim 1500$). This excess is present in the data of the CBI experiment (Bond et al., 2002) at 30 GHz, but has not been detected yet by independent experiments. Is this SZ effect from unresolved clusters ? Only new measurements at different frequencies can provide further insight.

3. A lot still to be done

The final proof of Inflation would be the detection of the B-modes in the CMB polarization (Kamionkowski & Kosowski, 1998). This is an incredibly difficult task, and we will give in the following a road-map to this measurement. There are, however, other issues to be investigated experimentally.

The mysterious Ω_Λ is now necessary to explain CMB measurements, independently of the SN measurements. This issue, one of the most important in physics today, should be attacked from several fronts. Measuring better the power spectra $\langle TT \rangle$, $\langle TE \rangle$, $\langle EE \rangle$, we can get more accuracy on Ω_Λ, and we can try to see the effect of the equation of state, i.e. measure w to discriminate between cosmological constant, quintessence or other hypothesis. Measuring better the high redshift supernovae we can do the complementary part of the exercise. The SNAP satellite (Aldering et al., 2003) is expected to provide great results in the future. An Antarctic optical telescope devoted to this search during the Antarctic winter could be a wonderful precursor, taking advantage of the minimal sky background present in Dome-C.

While the current limit $w < -0.78$ at 95% C.L. points against quintessence, the enhanced temperature fluctuations expected at large angular scales in a high Ω_Λ universe are missing. The game to play is to derive all the parameters with even better accuracy, by measuring better the high multipoles region of the $\langle TE \rangle$ and $\langle EE \rangle$ spectra. This is one of the missions of B2K, the polarization sensitive version of BOOMERanG (see Masi et al., 2003). It should also be noted that alternative models (not requiring Ω_Λ) are being developed (see e.g. Blanchard et al. (2003), where a model with only dark matter and baryons is considered). These models are not successful yet, but theorists are working very hard on this subject. Confirmation of the large scale anisotropy measurements of WMAP from independent experiments at different wavelengths should be considered. A single spinning balloon flight like Archeops (Benoit et al., 2001) with many 0.1K bolometers at 150 GHz and $\sim 5^o$ beams could give large scale anisotropy measurements competitive and complementary to the WMAP ones.

An orthogonal approach is the study of evolution of clusters of galaxies at high redshift, by means of the Sunyaev-Zeldovich (SZ) effect. Simulations show that the background from unresolved SZ clusters is very sensitive to Ω_Λ, due to the different cluster formation history (see e.g. Da Silva et al. (2000)). The SZ brightness scales as the density of the intracluster gas, while the X ray brightness scales as the density squared. There are two consequences of this fact.

The first one is that using the SZ we can detect clusters at higher redshift than using the X ray surveys. Clusters at high redshift appear small (of the order of 1 arcmin). A large telescope is required. An 8m telescope is being developed at South Pole, mainly with the target of measuring the SZ of a large sample of clusters at high redshift (Papitashvili, 2003).

The second consequence is that it is possible to study the peripheral regions of the cluster, where matter has not virialized yet and is accreting in the cluster. These peripheral surveys can produce very important information for structure formation and Ω_{DM}. This is an important task for smaller size telescopes: a survey of a selection of closeby clusters to be studied at many frequecies and in detail. Observations at cm and mm wavelengths from the ground (and particulary from Antarctica) and in the sub-mm from balloon or satellite (see e.g. Masi et al. (2003)) are needed to complete this survey. These measurements will also address the issue of anisotropy excess at multipoles ~ 2500. The same measurements will be used for the study of the anisotropy of the far infrared background generated by early galaxies (Hauser and Dweck, 2001).

For all these issues, sub-mm is the place to be: besides the South Pole 8m Telescope, sub-mm telescopes in unique locations like Dome-C, possibly implementing interferometry in order to have orthogonal systematics, can do an extremely good job. Balloon-borne telescopes in long duration flights around Antarctica, like BOOMERanG, OLIMPO and BLAST will explore the remaining part of the mm/sub-mm spectral range.

4. A road map to the measurement of B-modes

The power spectrum of polarization generated by B-modes is extremely faint: we expect signals in the range of $\lesssim 0.3\mu K$ (compare to the $\sim 100\mu K$ of $< TT >$, the anisotropy power spectrum). The level of the B-modes depends on the characteristic energy scale of inflation: its our only hope to sample the field responsible for inflation. The measurement does not require high angular resolution (a fraction of a degree is sufficient). The pattern is very distinctive (curl) and mathematical techniques exist to separate it from the total polarized signal and take into account finite sky coverage.

Since the B-modes are so faint, other phenomena can mimic it:

- Cross polarization in the instrument. Cross polarization must be controlled to better than 0.01% , otherwise the $< TT >$ and $< EE >$ signals mix to and dominate the $< BB >$ power spectrum ((Masi et al., 2001 a)).
- Foregrounds. The issue of foregrounds is particulary relevant. One of the best frequencies for bolometric receivers is 150 GHz (see e.g. the BOOMERanG results). We can naively predict the level of B-modes contamination from interstellar dust at this frequency. In fact, from BOOMERanG we know that at high Galactic latitudes the power spectrum of ISD anisotropy is about 1% of the power spectrum of the CMB (Masi et al., 2001 b). Moreover, recent measurement at 350 GHz by Archeops show that the polarization of the diffuse component of dust is around 10% of the intensity (Benoit et al., 2003 c). This will be composed by B-modes and E-modes. So we can naively expect a power spectrum of B-modes from ISD at the level of $\lesssim 10^{-4}$

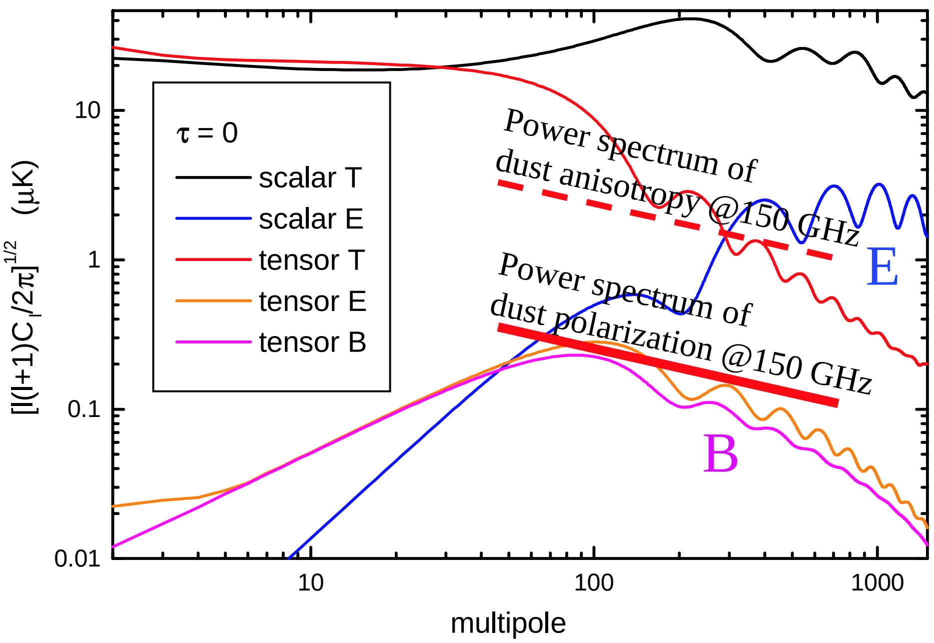

Fig. 2. $< TT >$ (top line), $< EE >$ (label E) and $< BB >$ (label B) power spectra of the CMB. For $< BB >$ it has been assumed a ratio of tensor to scalar pertrubations $T/S \sim 1.4$. Current limits are about 3 times lower ! The dashed thick line represent the power spectrum of CMB anisotropy at high Galactic latitudes, as measured from the BOOMERanG data at 150 GHz. The thick line represents a naive guess of foreground B-modes from diffuse interstellar dust, at high Galactic latitudes, at 150 GHz.

of the CMB anisotropy power spectrum. This is comparable to or larger than the expected B-modes of the CMB (see fig.2). A careful measurement of the foreground at high latitudes is required. After recovery, B2K could be refurbished filling the focal plane with a large number of polarization sensitive detectors, and reused to make a survey of dust polarization in the clean regions at high Galactic latitudes.

- Weak lensing from structures in the nearby Universe slightly deforms the CMB field, producing shear-like patterns which convert E-modes into B-modes. This effect is expected to dominate over the intrinsic B-modes of the CMB at multipoles $\ell \gtrsim 100$ (Zaldarriaga and Seljak, 1998).

It is evident that measuring B-modes is a formidable challange, promising crucial informations for cosmology and fundamental physics. There is a general agreement that the Planck satellite of ESA will provide a detection of B-Modes, and that a next generation CMB mission should be developed after Planck, in the time frame 2010÷2015.

Pathfinders are needed in the near future, to test the critical issues listed above. Comparing independent experimental approaches will be the only way to confirm the results.

Two nicely complementary experiments are BICEP from South Pole (Keating et al., 2003), and the B-modes experiment from Dome-C (Piccirillo et al., 2003). The first one is a regular polarimeter, while the second one is an interferometer. Both use bolometers to get the maximum possible sensitivity. Given the orthogonal optical arrangement, the two systems will be subject to very different systematics. If the results of the two experiments will be consistent, the detection will be considered a solid one.

5. Conclusions

Outstanding issues are evident in cosmology, now more than ever. New measurements in CMB are required and planned to solve them. Antarctica, and in particular the Dome-C base, will provide a great opportunity for mm/sub-mm cosmology.

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