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Polarization of the diffuse background radiation in the microwave region

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Abstract. We review the major advance in cosmology due to the detection of polarization in the cosmic background radiation by DASI and WMAP. We discuss the implications of available data, in particular for the cosmic thermal history at redshifts of a few tens; and the prospects for the forthcoming space experiments, also in connection with Galactic foreground contamination and cosmic-variance limits.

Key words. Cosmic background radiation – Polarization

1. Introduction

After a long series of experiments culminating with the Wilkinson Microwave Anisotropy Probe (Bennet et al. 2003), more than 30 (not independent) cosmological parameters are listed as the output of CMB data. Most of them are derived from the angular spectrum of temperature anisotropies. However, the inspection of the data table in WMAP's homepage[1] shows that most cosmological parameters regard the global structure and matter-energy contents of the Universe and the early times $z \sim 10^3$, but little information is provided on redshifts $z \sim 10-30$. This epoch, referred to as the Cosmological Middle Age, is fundamental to establish the connection between the primordial Universe and the observed astronomical structures, and provides the main field where measurements of CMB polarization are of crucial importance. Other important applications regard the gravitational wave background expected to originate from inflation, and the nature of dark energy; we also expect polarization data to help with cosmological parameter fits and degeneracy removal, and with the open problem of the weak low-order harmonics in CMB anisotropies.

2. The present knowledge on CMB polarization

Cosmological inferences from CMB are usually drawn using angular power spectra (APS) defined as $C_{Xl} =< a^*_{Xlm} a_{Xlm} >$, where a_{Xlm} is the harmonic amplitude of quantity $X = T$, E and B, with E and B the even and odd parts of the (Q, U) polarization field. Also the cross-correlation APS $C_{TEl} =< a^*_{Tlm} a_{Elm} >$ can be measured. The expectation values of C_{Xl} are computed by the publicy available[2] code CMBFAST for models of cosmic perturbations spectra, including adiabatic perturbations

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

[2] http://www.physics.nyu.edu/matiasz/CMBFAST/cmbfast.html

and other density waves, gravitational waves, strings and gravitational lensing. Actual realizations of the models for any local observers are affected however by stochastic fluctuations (cosmic variance), which are more important for low-order multipoles.

In Fig. 1 we show the E and TE APS arising from a scale-invariant adiabatic perturbation spectrum in the concordance model, i.e. the best cosmological model (including both dark matter and dark energy) selected by CMB data and suitable "priors" arising from other astronomical data. The concordance model, strictly speaking, does not fix the large-scale behaviours of both APS, which are strongly affected by the existence and features of a reionization (or reheating) of the cosmic medium in the Cosmological Middle Age. The B mode is not generated by linear density waves, and its presence in CMB – if not simulated by foregrounds – would be the inprint of primordial gravitational waves (on large scales), and of gravitational lensing or non-linear processes (on small scales).

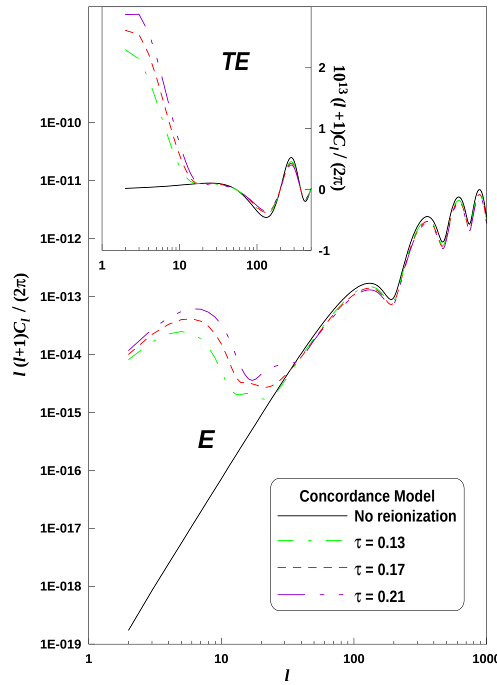

Fig. 1. The E and TE APS, computed by CMBFAST for a scale-invariant spectrum of adiabatic waves in the concordance model. For reionization optical depths $\tau > 0$ a sudden reheating is assumed.

2.1. DASI and WMAP results

The first positive measurement of CMB polarization (Kovac et al. 2002) was due to the Degree Angular Scale Interferometer (DASI), observing two 3.4° × 3.4° fields in ten frequency bands in the 26-36 GHz range. Signals in the two fields were subtracted to eliminate local contaminations: Therefore maps of CMB could not be provided, but only the APS on the assumption of uncorrelated signals; the foreground contamination was declared to be negligible in comparison to noise. The interferometer was sensitive to the angular range $l = 140 - 900$, but due to the high noise level the data analysis considered five flat angular-scale bands. The E and TE APS were detected at a fair signicance level in the $l = 245 - 420$ band, where both spectra were expected to exhibit the first primordial (i.e., not linked to reionization) peak; moreover, the consistency of results for all of the angular bands, as well as the lack of any evidence for a non-zero B-parity APS, support the claim that the polarized signal from

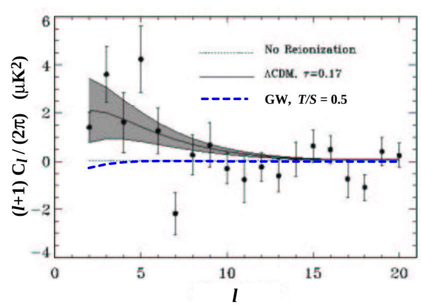

Fig. 2. The large-scale portion of the measured TE APS compared to the $\tau = 0.17$ reionization model, with the grey band denoting cosmic variance. A gravitational wave APS is superposed to the picture made available by WMAP's Science Team.

adiabatic perturbations has been detected in agreement with the concordance model.

DASI has not added anything to the physical scenario emerging from anisotropy experiments. A rather unexpected result, on the other hand, comes out from WMAP, reporting a full-sky coverage of the diffuse background at five frequencies between 23 and and 94 GHz, with resolutions ranging from 50′ to 13′ (Kogut et al. 2003). Although the radiation was splitted in two orthogonal polarizations at each point of the sky, differences were made for points about 140° apart, so that polarization maps have not been provided, at least in the first data release of year 2003. However the 2-point cross-correlation $C^{TQ}(\theta)$ could be measured, and modelled as a simple superposition of CMB and a foreground with a constant spectral index. From the frequency-independent part of $C^{TQ}(\theta)$ the TE APS is derived as shown in Fig. 2. The large TE cross-correlation was readily interpreted as due to a strong reionization of the cosmic medium with a Thomson-scattering optical depth

$$\tau = 0.17 \pm 0.04, \quad 68\% \text{ C.L.} \tag{1}$$

A best-fit model taking into account all of WMAP's data however provides larger error bars Spergel et al. (2003). Both treatments assume a sharp onset of reionization with a ionization degree $x_e = 1$. With this assumption Eq. 1 implies a reionization redshift $z_{\rm r} = 20^{+10}_{-9}$. It should be stressed however that this number is heavily model dependent, and moreover, the treatment of foregrounds was less refined here than in the rest of WMAP's data analysis.

3. Scenarios for the Cosmological Middle Age

WMAP's result, interpreted as in the previous Section, requires an early energy input in the cosmic medium. Reionization models involving UV emission from Pop-III stars or QSOs were studied since the Eighties (Couchman and Rees 1986) and during the Nineties (Haiman and Loeb 1997; Gnedin and Ostriker 1997), but typically provided moderate optical depths, $\tau \approx 0.05$. Introducing an early Pop-III generation with a star excess in the IMF at $M > 5M_\odot$ can boost the predicted τ up to the value of Eq. 1 (Ciardi et al. 2003). However, the increase of the Lyα forest opacity around $z = 5 - 6$ due to the Gunn-Peterson effect (Djorgovski et al. 2001; Becker et al. 2001) is in sharp contrast with models of this kind, where $x_e = 1$ already at $z \simeq 12$. A new scenario recently began to emerge, involving two different epochs and source types for reionization, and a partial recombination between the two (Cen 2003). Since then, double reionization models attempting to reconcile WMAP's and QSOs' data have been worked out by many authors; rather favourable assumptions on the efficiencies of star formation and ionizing photon escape have often been adopted (Wyithe and Loeb 2003), while other works (Sokasian et al. 2003; Ricotti and Ostriker 2003a) provided more refined treatments of radiative transfer and hydrodynamical simulations. In all of the models a very important issue is the epoch of the transition from Pop-III (with top-heavy IMF) domination to the normal star regime. Taking into account the Supernova feedback destroying Pop-III domination, it seems rather problematic to get $\tau \approx 0.17$ except for an extreme efficiency of UV emission. In this case one finds also a high efficiency of black hole formation $f_{BH} \approx 30\%$ (Ricotti and Ostriker 2003a).

Although the above extreme scenario cannot perhaps be excluded, one should ask whether some alternative to UV efficiency stretching is viable: Pop-III models might neglect important sources of ionization. For instance, ionizing emission from black hole accretion might produce the required opacity by itself (Ricotti and Ostriker 2003b). A decaying sterile neutrino of mass ∼ 200 MeV, too, might suffice (Hansen and Haiman 2003); however, such a mass is quite smaller than suggested by high-energy physics. Also, quantitative predictions of the TE APS are affected by the underlying cosmology, in particular by the time evolution of the cosmic scale factors, which in turn depends on the equation of state of dark energy. The TE shape can be strongly changed with a time-varying equation of state, as arising from Ratra-Peebles and SUGRA potentials (Mainini et al. 2003). However, it seems difficult to produce a large positive TE cross-correlation in this way.

We should finally ask, whether the first-release WMAP team's analysis is really definitive. Fitting the high-z QSO data from the SDSS together with WMAP (Chiu et al. 2003) gives a smaller opacity, $\tau = 0.11^{+0.02}_{-0.03}$, still consistent with the large error bars declared by Spergel et al. Therefore, we think that we should not put too much weight to the reported best value of τ. On the other hand, it is very likely that primeval sources generated a cosmic opacity larger than expected from naive consideration of the Gunn-Peterson test. A magnified source in the gravitational-lensing cluster A 1835 (Pelló et al. 2004) has been recently proposed as a good candidate for being a $z = 10$ Pop-III galaxy with a top-heavy IMF Ricotti et al. (2004). This might be the first detected example of the primeval galaxies which (at still higher redshifts) drove the first reionization of the Universe.

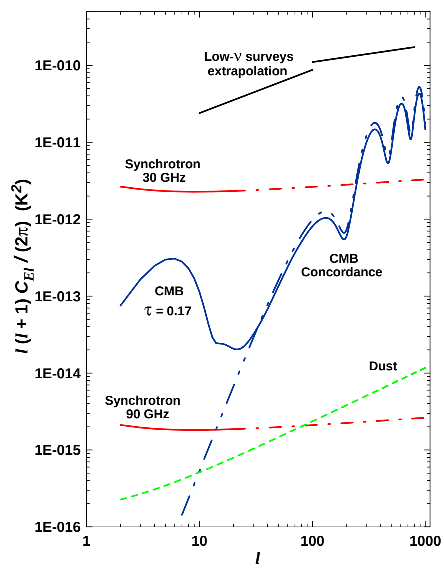

Fig. 3. Synchrotron E-mode APS compared to CMB and dust. The 30- and 90-GHz APS are fitted on templates (Bernardi et al. 2004) for $l < 25$ and extrapolated to higher l, except the 30 GHz extrapolations from 0.4-1.4 GHz surveys. The dust APS was derived from a polarized dust emission template (Prunet et al. 1998).

4. Forthcoming space experiments

Further data on large angular-scale polarization are required to assure that the reported low-l peak in the TE cross-correlation is entirely genuine. During the writing of this paper, WMAP's 2nd release is still waited for; moreover some ground and balloon experiments are in progress or under analysis (e.g., polarimetric Boomerang and BaRSPOrt). However, a substantial progress will probably be provided only by space experiments which, in order to safely exclude spurious effects, must directly detect the E-parity APS in the low-l region. In this connection, we should be aware that the final accuracy of a CMB polarimetric experiment is not necessarily determined by the noise level: It may heavily depend on the ability to control or remove instrumental spurious polarization, systematics and foregrounds.

4.1. The foreground contamination

In the microwave region the main polarized foreground is Galactic synchrotron. Since direct measurements are not yet available in the cosmological window, templates have been built at frequencies between 23 and 90 GHz (Bernardi et al. 2003, 2004) using the following ingredients: (a) Total intensity distributions (mainly the 23 GHz WMAP's synchrotron map cleaned from other foregrounds), (b) a "polarization horizon" model to derive polarized intensity, (c) the polarization vector field from starlight, and (d) a varying spectral index field. E-parity APS computed on templates at 30 and 90 GHz are shown in Fig. 3. At DASI's frequencies the synchrotron contamination for $l = 200 - 300$ appears to be not negligible over the largest part of the sky. On the other hand, no Galactic foreground problem should exist at 90 GHz for the detection of the E-parity mode, in particular in the scale region of the reionization spectral bump. For the contamination of the B-parity APS, the situation is more complex (Bernardi et al. 2004).

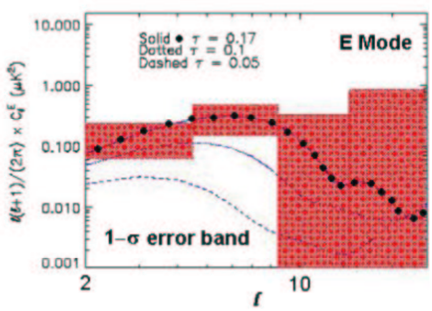

Fig. 4. SPOrt's 1-σ error belts, including cosmic variance, for three power bands of E-mode APS.

4.2. SPOrt

If further releases of WMAP do not offer some new surprise, the first space experiment having a good chance to detect the large-scale E signal is the Sky Polarization Observatory (SPOrt), which is planned to fly onboard the International Space Station in 2006. SPOrt will cover 80% of the sky at 22, 32 and 90 GHz with a 7° resolution and a pixel sensitivity to each CMB Stokes parameter of 1.7 μK ; differing form the WMAP design and the Planck project, its polarimetric design[3] warrants a substantial identity of noise limit and true accuracy in measuring the Stokes parameters of CMB. SPOrt's band power spectrum sensitivity is shown in Fig. 4. A non-null measurement of the rms polarized signal $P_{\rm rms}$ is warranted at a 95% C.L. even for $\tau = 0.1$. Further, a joint exploitation of SPOrt's output and available anisotropy data would help to remove parameter degeneracies (Cortiglioni et al. 2004).

4.3. Planck and beyond

The design of LFI and HFI as described in Planck's homepage[4] includes more than 80 polarized detectors: although some design details are being changed, it still gives a good idea of the expected performance. The frequencies relevant for CMB polarization (in the range 30-143 GHz) are covered with resolutions of $33' - 8'$ and pixel sensitivities of $4 - 12$ μK; the declared sensitivities do not explicitly take into account the efficiency in removing spurious polarization, but it is quite clear that this experiment, which is planned to fly in 2007, will provide a very substantial progress in the knowledge of CMB polarization. In particular, Planck is expected to investigate the E and TE APS for l of order a few tens with an accuracy not far from the cosmic variance limits. According to semi-analytic modelling (Holder et al. 2003), achieving this goal for E mode will suffice to distinguish details of the reionization history. In particular, the total optical depth τ and the initial reionization redshift $z_{\rm r}$ will be tested as independent parameters. It has also been noted (Skordis and Silk 2004) that, since the polarization harmonics are generated by the temperature quadrupole, the latter can be inferred better than the cosmic variance limit by measuring about 30 C_{El}. More precisely, the E-mode APS probes the contribution to the quadrupole from the reionization epoch; this can be regarded as even more informative than the accidental realization of the temperature quadrupole seen by us here and now at $z = 0$, and would provide very valuable knowledge in the light of the well-known deficit of large-scale anisotropies.

On the other hand, a clean measurement of the B mode and the assessment of the cosmological gravitational wave background will probably require a post-Planck mission. According to the available synchrotron templates (Bernardi et al. 2004), in order to achieve this goal a substantial progress in the knowledge of the Galactic foreground will also be required.

[3] http://sport.bo.iasf.cnr.it

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

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