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Cosmic Microwave Background as a reionization probe

Nabila Aghanim & Jean-Loup Puget
Institut d'Astrophysique Spatiale, Bâtiment 121,
Université Paris Sud, 91405 Orsay, France

We are now in a new era of precision cosmology that enables us to use the Cosmic Microwave Background (CMB) temperature and polarisation anisotropy measurements to constrain the cosmological parameters and the underlying theoretical models. From all the CMB experiments, a firm detection of the acoustic peaks in the CMB temperature power spectrum, a measurement of the temperature-polarisation cross-correlation as well as the E-mode low multipole spectrum have been obtained. In the framework of adiabatic cold dark matter models, this provides strong evidences for the inflationary predictions and sheds new light on various cosmological parameters.

Future CMB experiments will be even more powerful as they are designed to achieve n more evaccurate measurements of temperature anisotropies down to a few arcminute scales as well as polarisation measures. CMB measurements will be quite useful to probe astrophysically induced effects like thoses associated with secondary anisotropies and reionisation. After matter and radiation decoupled around $z = 1100$, universe became neutral with a low residual ionisation fraction of about 10^{-4}. Observations of the the Gunn-Peterson thoughts (e.g. Fan et al. 2003) in the line of sight of quasars with redshifts as high as ~ 6.5 however show that the universe is ionised. The transition underwent by the universe from neutral to ionised state is called reionisation. Recently, CMB observations have added constraints on reionisation. Through the measurement of the cross-correlation between temperature and polarisation signals (Kogut et al. 2003) and more recently through the measure of the polarised signal (Page et al. 2006), we have good contraints on the value of the Thomson optical depth $\tau \simeq 0.09$. Reionisation most likely occured when first emitting sources formed. We still do not know precisely what are the sources that powered it, when reionisation did it exactly occur and how long did it take?

In the following, we briefly review the effects of reionisation on the CMB temperature and polarisation anisotropies both on large and small angular scales. The reionisation process needs to be known in detail if one wants to use the CMB signal as an observational probe of the early universe. We briefly review some fundamental issues for which reionisation plays an important role. We show that reionisation needs to be understood and modelled for its own sake but also for cosmological studies.

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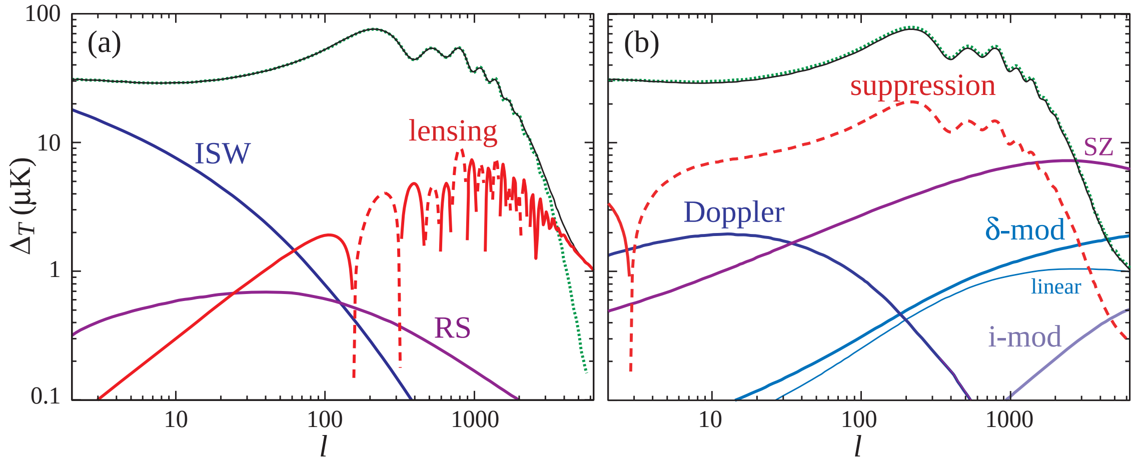

Figure 1: From Hu & Dodelson (2002), panel (a) represents the secondary effects from gravitational interaction. Panel (b) shows the effects of reionisation: supression of primary (dashed), and secondary additional fluctuations

1. Effects of reionisation on CMB anisotropies

At reionisation interactions between CMB photons and free electrons randomise the directions of propagation of the fraction of rescattered photons. As a result, some of the primary CMB anisotropies are suppressed and the power in the acoustic peaks is damped by a factor $\exp(-2\tau)$. At the same time, the scattering with electrons moving along the line of sight, with velocity $v_{\rm r}(\theta,t)$, generates secondary anisotropies through Doppler effect (see Fig. 1). Their amplitude is given by:

$$\frac{\Delta T}{T}(\theta) = \int \mathrm{d}\eta\, a(\eta) g(\eta) v_{\rm r}(\theta,\eta) = -\int \mathrm{d}t\, \sigma_{\rm T} \mathrm{e}^{-\tau(\theta,t)} n_e(\theta,t) v_{\rm r}(\theta,t) \qquad (1.1)$$

The electron density can be written as $n_e(\theta,t) = \bar{n}_e(\theta,t)[1+\delta+\delta_{\chi_e}]$, with $\bar{n}_e(\theta,t)$ the average number of electrons and δ and δ_{χ_e} the fluctuations of density and ionisation fraction respectively. Equation 1.1 shows that there are two second order effects which affect the probability of scattering of the CMB photons (e.g. Dodelson & Jubas 1995) and generate secondary anisotropies. They are referred to as modulations of the Doppler effect (i.e. the velocity field) by density and ionisation spatial variations. The second effect is commonly referred to as the inhomogeneous or patchy reionisation (e.g. Aghanim et al. 1996). The first effect is usually called Ostriker-Vishniac effect (Ostriker & Vishniac 1986) in the linear regime. The non-linear regime corresponds to the kinetic Sunyaev-Zeldovich (KSZ) effect (Sunyaev & Zeldovich 1980) and is usually caused by interactions with ionised gas in collapsed structures like galaxy clusters. Secondary temperature anisotropies (see Fig. 1), in particular those arising from the linear regime and the inhomogeneous reionisation, are additional observational probes of reionisation. However, since their amplitudes are much smaller than other secondary anisotropies generated on similar scales (e.g. KSZ and thermal Sunyaev-Zeldovich) or than primary anisotropies, they are difficult to use in practice to constrain reionisation models.

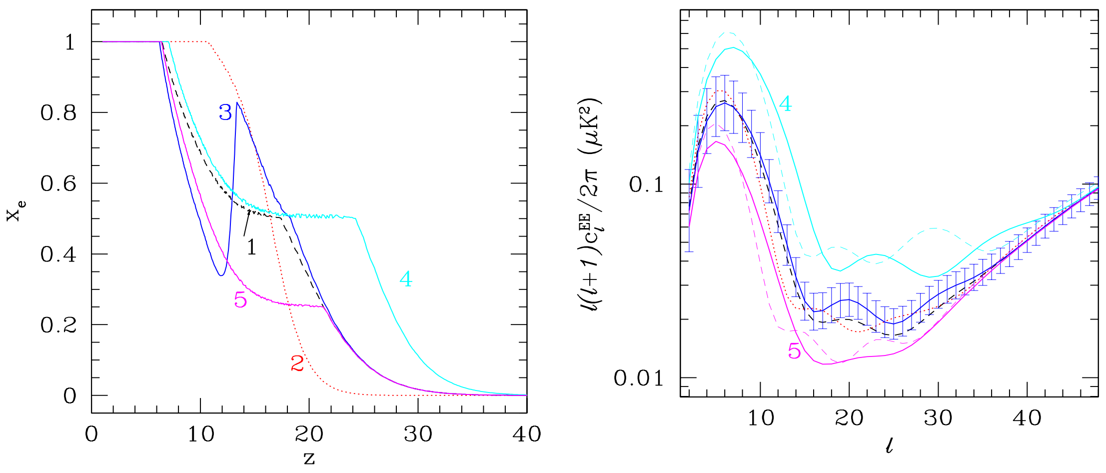

Figure 2: From Holder et al.(2003), left panel is the ionisation fraction and right panel the polarisation spectrum for diffrent reionisation models

Another aspect of reionisation is the induced polarisation. The CMB radiation posses a primary quadrupole moment. Thomson scattering between the CMB photons and free electrons thus generates linear polarisation both at recombination and reionisation. In the latter, photons rescattering generate a new polarisation anisotropy at large angular scale (see Fig. 1, solid thick line) corresponding to the horizon size at reionisation (Ng & Ng 1996). It results in a bump in the E-mode polarisation power spectrum which location depends on the ionisation redshift $z_{\rm ion}$ (e.g. Liu et al. 01). Such a bump can also be observed in the correlation between temperature and E-mode polarisation with an amplitude proportional to τ. The E-mode polarisation signal is, in turn, proportional to τ^2. In addition to $z_{\rm ion}$ we can thus have insight on the optical depth τ through the height but also the width of the bump. Precise measurements (cosmic variance limited) of the E-mode polarisation power spectrum allow us to five uncorrelated numbers associated with the eigenmodes of the reionisation history (e.g. Hu & Holder 2003). This helps in tightly constraining the reionisation models and distinguishing the transition between partial and total reionisation (e.g. Holder et al. 2003). Planck will constrain partial or double reionisation to the percent level discriminating between different models with identical optical depths (Kaplinghat et al. 2003). Similarly to the temperature case, secondary polarisation is generated at small angular scales at reionisation. The signal, computed both analytically (e.g. Santos et al. 2003) and using numerical simulations (e.g. Liu et al. 2001), was found too small to be detected by the present and near future CMB experiments (see Fig. 1, thin dashed, dotted and solid lines).

2. Probing the early universe through reionisation

Measuring the CMB temperature and polarisation anisotropies is obviously a very good tool to probe reionisation models. Furthermore, a perfect measurement and understanding of reionisation (duration and epoch) are needed for primordial universe studies. CMB temperature and

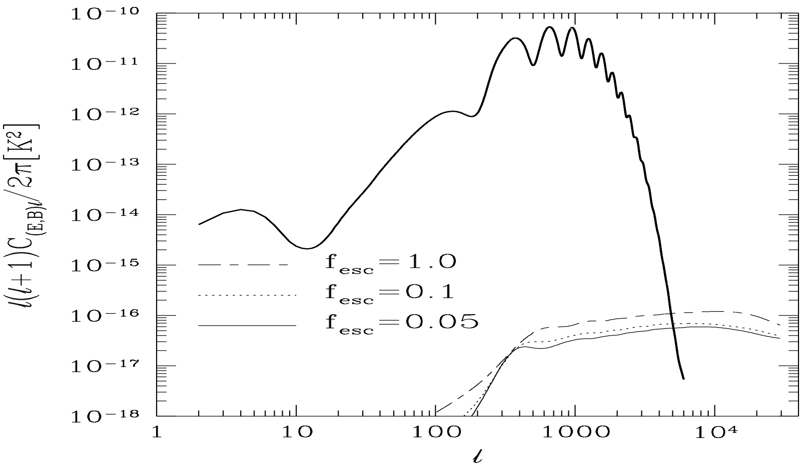

Figure 3: From Liu et al.(2001), polarisation power sepectra from primary signal (solid thick line) and from secondary effects for different reionisation models (thin dashed, dotted and solid lines)

polarisation anisotropies indeed trace the early universe through probing inflation and measuring the cosmological parameters.

The temperature/E-mode polarisation anti-correlation observed around $\ell = 30$ indicates that inflation is the likely origin for the primary perturbations (e.g. Spergel & Zaldarriage 1997, Peiris et al 2003). However, the tilt of the primordial power spectrum inferred from CMB observations is degenerate with the reionisation optical depth. Additionally, secondary anisotropies induced by reionisation generate small scale anisotropies which add to primary CMB. As a result, future tests of inflation through the spectral index value n_s and its running need quite a good knowledge of the reionisation process and effects. Furthermore, the normalisation of the initial power spectrum is degenerate with the damping of the temperature anisotropies, in other words with τ.

The B-mode polarisation signal is a unique observational tracer of the stochastic gravitational wave background which in turn probes the energy scale of inflation (e.g. Starobinsky 1979, Mukhanov 2005). The expected signal is quite small at $\ell < 10$. At intermediate scales, around $\ell = 100$, the primary signal superimposes to secondary B-modes converted from E-modes by weak lensing on large scale structures. Here again reionisation is quite important since it enhances the B-mode signal at large scales ($\ell < 10$), the horizon scale at reionisation. As a matter of fact, the same free electrons producing the E-mode bump at small multipoles scatter the quadrupole produced by the tensor modes (gravitational waves). They produce a bump with an amplitude proportional to τ^2. Reionisation therefore eases the measurement of the B-mode primary polarisation (e.g. Kaplinghat et al. 2003). However, a good measurement of both τ and n_s, and its tilt, is needed to constrain the so-called scalar to tensor ratio.

Decaying particles remain an option for reionisation that is quite hard to constrain. One example is decaying sterile neutrinos (e.g. Boehm et al. 2004) whose decay products, relativistic electrons, induce partial ionisation. Reionisation is then completed by subsequent star formation at lower redshifts. Neutrino with a mass of ~ 200 MeV and a decay time of $\sim 10^8$ yrs can account for an optical depth as high as 0.16 without violating existing limits on the gamma-ray backgrounds (Hansen & Haiman 2004). Partial reionisation by sterile neutrinos leave specific imprints on the temperature and polarisation CMB anisotropies that can be observed with future precise measurements with Planck (Padmanhaban & Finkbeiner 2005).

3. Conclusions

Reionisation is intimately linked to the end of the dark ages and the formation of the first objects whose ionising photons consumed the neutral hydrogen atoms. It is one of the less known epochs of the evolution of the universe. Most associated questions remains unknown. As a matter of fact, we do not know what is the source of ionising photons. Do particles contribute to the ionising budget or is the latter related to the first emitting objects only? What are these objects: mini-Black Holes, metal free massive pop III stars, starburt galaxies? We do not know neither when did the reionisation occur, if it was instantaneous and if not and how long it lasted.

Probing the reionisation of the universe requires to use different observational signatures. Ultimately, the CMB data (polarisation and temperature) in combination with other direct or indirect observational probes like 21cm emission and Lyα absorption by neutral HI, metal abundances, X-rays, infrared background or Gamma ray bursts will permit a detailed reconstruction of the physics of reionisation.

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