Mem. S.A.It. Vol. 79, 969

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Studying reionization with secondary CMB anisotropies

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Abstract. It is an open question in Cosmology how the process of reionization happened and how the first galaxies and cosmological structures formed. Known probes of reionization are: Cosmic Microwave Background (CMB) polarization, observations of neutral hydrogen 21 cm hyperfine line, or direct observation of the first galaxies. Here we concentrate on possible signatures of the metal enrichment of the inter-galactic medium from the first stars, through their effects on the CMB. Detailed signal-to-noise calculations still need to be carried out to find out wether these effects are accessible to balloon-borne experiments.

Key words. Cosmology: observations, cosmic microwave background

1. Introduction

After recombination the universe is filled with neutral Hydrogen and thus opaque to UV and optical observations. At $z \sim 10$ the universe is ionized by the radiation of the first stars, ending the *dark ages*. During reionization, metals are produced for the first time and they enrich the inter-galactic medium (Barkana & Loeb 2001). Here we concentrate on two signatures of metal enrichment of the inter-galactic medium by the first stars on the CMB: resonant scattering by metals and Oxygen pumping.

2. Resonant scattering by metals

CMB photons interacting with a species X at redshift z_{rs} via a resonant transition of resonant frequency ν_{rs}, show the effect of the interaction if $z_{rs} = \nu_{rs}/\nu_{obs} - 1$ (Basu et al. 2004). The resonant scattering of this species generates an optical depth to CMB photons (Sobolev 1946): $\tau_X(z) \propto f_{rs} n_X(z)$, where n_X is the number density of the X species and f_{rs} is the absorption oscillator strength. τ_X modifies temperature anisotropies: $\Delta_T = e^{-\tau_X}\Delta_{T_{orig}} + \Delta_{T_{new}}$. In the limit of low metal abundance $\tau_X \ll 1$, we can retain only linear terms in τ_X. Thus (Basu et al. 2004), the change in the anisotropies $(\Delta_T - \Delta_{T_{orig}})$ reduces to a *blurring* factor $(-\tau_X \Delta_{T_{orig}})$ plus a new term which is important only in the large scales and which we neglect here. In multipole space, $\Delta a_{\ell m} = -\tau_X a^{CMB}_{\ell m}$ with a well defined frequency dependence: in the presence of only one resonant species at z_{rs} the effect will be non-zero only at frequency $\nu_o = \nu_{rs}/(1+z_{rs})$. Thus the metals contribution to the power spectrum is proportional to the primordial CMB power spectrum with constant of proportionality given by $\tau_{\nu_{rs}}$.

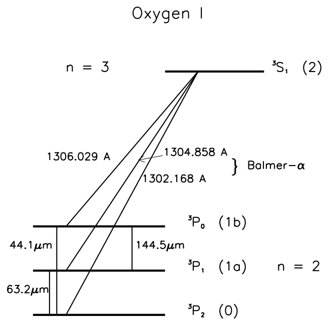

Fig. 1. Sketch of the transitons involved in the "oxygen pumping" mechanism.

In a given experiment, the lowest frequency channel corresponds to the highest redshift where the metal abundance is the lowest. Increments of metal abundances can be measured by studying the difference map and the difference power spectra between different channels. Signal-to-noise considerations (Hernández-Monteagudo et al. 2006) show that the main limiting factor is the accuracy of the cross-channel calibration. To conclude, a purpose-built experiment, with accurate control of systematics, might be sensitive to changes in 3-12% (2-σ) of the Solar fraction of Oxygen abundance at $12 < z < 22$ for reionizaton redshift $z_{re} > 10$ (OIII 84 μ m transition) and to changes in N abundance of 60% its solar value for $5.5 < z < 9$ (2-σ)(NII 205 μm transition). To achieve these constraints, beyond accurate foreground subtraction, a cross-channel calibration uncertainty better than one part in 10^4 is needed (like e.g., FIRAS or current Fourier Spectrometers).

3. Oxygen pumping

Oh (2002) suggested that OI may be present in fossil HII regions where short-lived ionizing sources have turned off. The filling factor of such fossil HII regions can be large prior to full reionization (Oh & Haiman 2003).

The 63.2μm fine structure line of OI can be pumped by the $\sim$ 1300Å soft UV background produced by the first stars, via the OI Balmer α line. This is analogous to the Wouthuysen–Field effect for exciting the 21cm line of cosmic HI (Hernández-Monteagudo et al. 2007). See fig 1. This process of *Balmer α pumping* modifies the occupation of the levels involved and therefore introduces a shift in the spin temperature T_S, so that it slightly departs from the CMB temperature, T_{CMB}. The form of the UV background spectrum implies $T_S > T_{CMB}$, producing an excess of 63.2 μm photons. OI at redshift z should be seen in emission at $(1 + z)63.2\mu$m, and for $7 < z < 10$ it would produce a spectral distortion of the CMB, in principle detectable through a precise future measurement of the CMB spectrum (Fixsen & Mather 2002). This would open the possibility of performing tomography of the metal distribution. OI 63.2μm (and 44.1μm) transition could be seen as deviations in the CMB black-body spectrum $\sim 10^{-8}$ at $160-500$ GHz (481 GHz corresponds to z=10 and 160 GHz to z=30, for the 63.2μm).

We find that the FIRAS data (Fixsen et al. 1996), in the range of frequencies corresponding to $10 < z_s < 20$ for the 63.2μm line, set an upper limit of 5 (40) solar metallicity at $z_s > 10$. Although not yet at an interesting level, this is the first *direct* constraint on the metallicity of the IGM in the universe at $z \sim 10$. The upper limit on the metallicity scales linearly with the constraint on y. For example, by comparing different, accurately calibrated Planck HFI channels, constraints $y < 5 \times 10^{-7}$ could be imposed. An experiment able to reduce the FIRAS y uncertainty (e.g., Fixsen & Mather 2002) by 2 to 3 orders of magnitude could impose interesting constraints.

4. Conclusions

We have presented two ways of studying reionization through secondary effects on the CMB which are highly complementary to other probes of reionization. The first approach, for example, is complementary to H-21cm observations as systematic effects will be of very different nature in the two cases. Foreground and systematics must necessarily be studied an controlled for experiments aiming at measuring primordial B-modes.It remain to be seen whether a balloon-born experiment can achieve the required signal-to-noise, systematic control and and stability. For example, in the second approach, to obtain interesting constraints, a dedicated experiment able to reduce the FIRAS y uncertainties by two to three orders of magnitude will be needed.

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