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21 cm radiation: a new probe of fundamental physics

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Abstract. New low frequency radio telescopes currently being built open up the possibility of observing the 21 cm radiation before the Epoch of Reionization in the future, in particular at redshifts $200 > z > 30$, also known as the dark ages. At these high redshifts, Cosmic Microwave Background (CMB) radiation is absorbed by neutral hydrogen at its 21 cm hyperfine transition. This redshifted 21 cm signal thus carries information about the state of the early Universe and can be used to test fundamental physics. We study the constraints these observations can put on the variation of fundamental constants. We show that the 21 cm radiation is very sensitive to the variations in the fine structure constant and can in principle place constraints comparable to or better than the other astrophysical experiments ($\Delta\alpha/\alpha =< 10^{-5}$). Making such observations will require radio telescopes of collecting area $10 - 10^6$ km^2 compared to ~ 1 km^2 of current telescopes. These observations will thus provide independent constraints on α at high redshifts, observations of quasars being the only alternative. More importantly the 21 cm absorption of CMB is the only way to probe the redshift range between recombination and reionization.

Key words. Cosmology: early Universe – Radio lines: general – Cosmology: diffuse radiation – Cosmology: observations – cosmic microwave background

1. Introduction

In the standard model of cosmology the electrons recombine with protons and heavy nuclei, mostly helium, to form neutral atoms at a redshift of around $z \sim 1100$. The mostly neutral baryonic gas then undergoes gravitational collapse to form the first stars which then reionize the Universe. The process of reionization is expected to start at around $z \lesssim 30$ and end by $z \sim 6$. The era between recombination and reionization has come to be known as the dark ages due to the absence of any stars or other light emitting collapsed objects. There is however the CMB which gets absorbed by the hydrogen gas at 21 cm rest wavelength corresponding to the hyperfine transition of ground state of hydrogen. The observation of these dark ages using the 21 cm line is considered to be the last frontier in cosmology due to the new information it will bring about this hitherto unexplored redshift range and also because the amount of information we can get from the 21 cm observations of dark ages is many orders of

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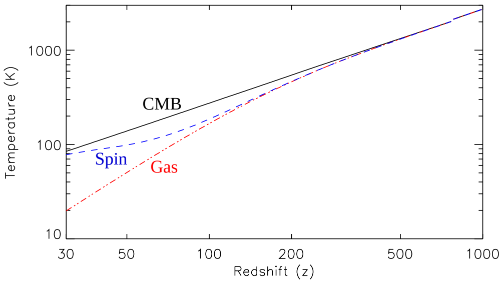

Fig. 1. Thermal history of the Universe. Collisions keep the spin temperature close to gas temperature at high redshifts while at low redshifts coupling to CMB pushes the spin temperature towards CMB temperature.

magnitude more than is possible by any other cosmological probe.

We can probe the big bang nucleosynthesis at a redshift of $z \sim 10^9$ by measuring the abundance of light elements, this gives information only about the average properties of the Universe. CMB is a snapshot of Universe at $z \sim 1100$ and has information on scales $\gtrsim 10$ Mpc. Below 10 Mpc Silk damping causes the CMB power spectrum to drop rapidly making it hard to measure. Observations of galaxies, clusters of galaxies and Lyα forest probes $z \sim> 6$ also on scales > 10 Mpc. On small scales the matter perturbations at low redshifts become non-linear making it hard to reconstruct the initial conditions or constrain fundamental physics. The 21 cm observations will allow us to probe a new redshift range of $30 \gtrsim z \gtrsim 200$, which is not accessible by any other method, on scales down to $\sim$ few kpc and use that information to constrain initial conditions and fundamental physics.

2. 21 cm cosmology

We refer to the review paper Furlanetto, Oh, & Briggs (2006) for the details of 21 cm cosmology. After recombination although most of the plasma has recombined, some residual ionization remains with ionization fraction $\sim 10^{-4}$. These remaining free electrons scatter off CMB photons transferring energy from the CMB to gas. The baryon temperature is thus maintained at that of CMB up to a redshift of $\sim$ 500 when Thomson scattering becomes inefficient in heating the gas and thereafter baryons cool adiabatically due to the expansion of the Universe. This is shown in Figure 1. Also shown in the figure is the spin temperature defined by relating the population levels in the two hyperfine states of hydrogen by the Boltzmann factor, $\frac{n_t}{n_s} = \frac{g_t}{g_s} e^{-T_\star/T_{spin}}$, where n_t and n_s are number density of hydrogen atoms in excited triplet and ground singlet state respectively, g_t and g_s are the corresponding statistical weights, $T_\star = 0.068K$ is the energy difference between the two levels and T_{spin} is the spin temperature. Its behavior can be understood as follows. At high redshifts the density of gas is high and the spin changing collisions between the hydrogen atoms is the dominant effect determining the population levels in two states establishing local thermodynamic equilibrium. Thus at high redshifts spin temperature is equal to the kinetic temperature of gas. At low redshifts as the density of gas drops collisions becomes inefficient compared to the absorption and emission of CMB photons in determining the population levels. The spin temperature thus approaches that of CMB. The mean observed brightness temperature defined by the Rayleigh-Jean formula $T_b = I_\nu c^2/2k_B\nu^2$, where I_ν is the intensity difference due to absorption/emission of 21 cm photons, is given by

$$T_b = \frac{(T_s - T_{CMB})\tau}{(1+z)}, \tau = \frac{3c^3\hbar A_{10} n_H}{16 k_B \nu_{21}^2 (H + \frac{dv}{dr}) T_s}$$

where τ is the optical depth, H is Hubble parameter, k_B is Boltzmann constant, n_H is number density of neutral hydrogen, $\nu_{21} = k_B T_\star / h \sim 1420$MHz, v is the peculiar velocity of gas and r is the comoving distance. As shown in Figure 1, between recombination and reionization the spin temperature is less than the CMB temperature which gives a negative T_b corresponding to absorption. The redshift of $200 \gtrsim z \gtrsim 30$ corresponds to the observed frequency range of 7MHz $\lesssim \nu_{\rm obs} \lesssim$ 46MHz. At around redshift of $z \sim 30$ first stars are expected to form which would heat and ionize the gas complicating the prediction of the 21 cm signal due to unknown astrophysics.

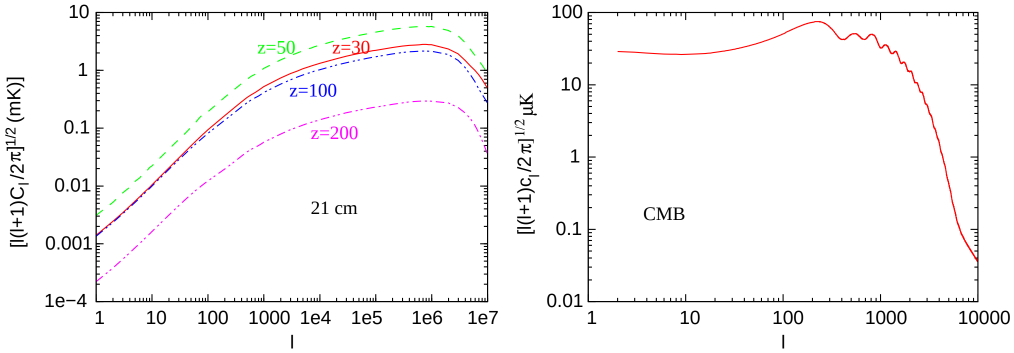

Fig. 2. 21cm angular power spectrum and CMB power spectrum. Numerical calculations were done using CMBFAST (Seljak & Zaldarriaga 1996)

Perturbations in the baryon density and temperature gives rise to perturbations in the 21 cm absorption signal and we can compute the angular power spectrum of the perturbations as in case of CMB (Bharadwaj & Ali 2004; Loeb & Zaldarriaga 2004). Figure 2 shows the 21 cm angular power spectrum for different redshifts. Also shown for comparison is the CMB angular power spectrum. The CMB power spectrum is suppressed due to free streaming of photons for angular wavenumber $\ell \gtrsim 3000$. Since the 21 cm power spectrum traces the matter density perturbations we can probe much smaller scales, $\ell \sim 10^6$. For $\ell > 10^6$ 21 cm power spectrum is also suppressed due to baryon pressure. Also we can measure 21 cm power spectrum at many redshifts, the number being determined by the bandwidth of the telescope. Thus 21 cm power spectrum probes a volume of the early Universe in contrast with CMB which probes a surface (of some finite thickness). The amount of information can be summarized by number of modes we can measure, which for 21 cm is $\sim \ell^3_{max} \sim 10^{16}$ compared with CMB which is $\sim \ell^2_{max} \sim 10^7$. Thus there is many orders of more information available, in principle, from 21 cm observations of dark ages. More importantly the perturbations are linear down to very small scales and can be accurately calculated and used to reconstruct initial conditions or constrain fundamental physics.

3. Fundamental physics with 21 cm radiation from dark ages

The enormous amount of information accessible with 21 cm observations of dark ages provides an opportunity to constrain fundamental physics with high precision, for example initial conditions of the Universe (Gordon & Pritchard 2009), grand unified theories and superstring theory physics (Khatri & Wandelt 2008) and variation of fundamental constants (Khatri & Wandelt 2007). One of the important questions in fundamental physics is whether the fundamental constants vary in space and time. Since 21 cm signal depends on atomic physics it can be used to constrain the related fundamental constants like the fine structure constant (α) and electron to proton mass ratio $\mu = m_e/m_p$. In fact 21 cm physics is highly sensitive to the variation in α. The rest frequency $\nu_{21} \propto \alpha^4$, Einstein coefficient $A_{10} \propto \alpha^{13}$, Thomson cross section $\sigma_T \propto \alpha^2$ and the ionization fraction x_e is determined by recombination physics which is also sensitive to α (Hannestad 1999; Kaplinghat, Scherrer, & Turner 1999). The α dependence of spin change cross sections due to collisions between hydrogen atoms needs to be calculated ab-initio (Khatri & Wandelt 2007) and is found to be $\kappa_{10} \propto \alpha^{2-8}$ where the index on α depends on gas temperature. Taking this α dependence into account we can do a Fisher matrix

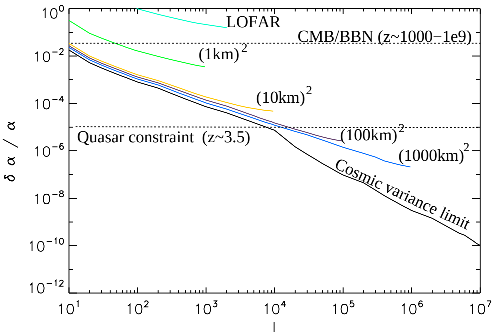

Fig. 3. Constraints on α from 21 cm observations of dark ages for different radio telescopes labeled by collecting area. Also shown is a current telescope, LOFAR, that is currently operating in Europe.

analysis (Zaldarriaga, Furlanetto, & Hernquist 2004) of constraints we can get on the variation of α . The result of such an analysis is shown in Figure 3. Different curves are for the radio telescopes of different sizes labeled by the collecting area (with the aperture filling factor assumed to be unity). Although current telescopes like LOFAR do not have enough collecting area to provide interesting constraints, a telescope few times bigger can surpass the CMB and big bang nucleosynthesis constraints while a telescope with a thousand square kilometer of collecting area will be able to surpass the current best quasar constraints.

4. Conclusions

We have shown that the 21 cm observations of the dark ages can provide very tight constraints on the variation of the fine structure constant. In addition we should also expect similar sensitivity to the electron to proton mass ratio. This is easily seen by observing that $A_{10} \propto \frac{1}{m_e^2}\left(\frac{m_e m_p}{m_e+m_p}\right)^3$, $\sigma_T \propto \frac{1}{m_e^2}$ etc. The spin change collision cross section also depend on m_e/m_p through the kinetic term in the electronic Hamiltonian of the hydrogen molecule. One of the challenges in observing this 21 cm cosmological signal is the presence of the synchrotron foregrounds. The sky noise due to the synchrotron foregrounds in the galaxy is expected to be $T_{sky} \sim 19000K\left(\frac{22MHz}{\nu}\right)^{2.5}$ (Roger et al. 1999). This is many orders of magnitude larger than the cosmological signal which is of the order of $\sim$ mk. The foregrounds can still be removed from the cosmological signal due to the following reason (Zaldarriaga, Furlanetto, & Hernquist 2004). The foregrounds are expected to be correlated in frequency while the cosmological signal traces a gaussian random field and would be uncorrelated for frequencies sufficiently separated. Thus the detection of the cosmological signal is challenging but possible. Interstellar scattering may limit the smallest scales that are observable to $\ell \lesssim 10^6$ (Cohen & Cronyn 1974). Terrestrial EM interference from radio/TV/communication and Earth's ionosphere poses problems for telescopes on ground. Earth related problems may be solved by going to the Moon and there are proposals for doing so, one of which is the Dark Ages Lunar Interferometer (DALI) (Lazio et al. 2009). In conclusion 21 cm cosmology promises a large wealth of data with which to constrain and learn about fundamental physics.

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