Probing the Epoch of Reionization with 21-cm Line

- Free protons and electrons recombined to form neutral hydrogen at z $\sim$ 1100 (the last scattering surface) and remained neutral during dark ages prior to the formation of the first ionizing sources. These sources which include pop III stars, galaxies and distant quasars started ionizing the universe at z $\sim$ 10 and completely ionized the universe by z $\sim$ 6. This is knows as the epoch of reionization(EoR). These first sources created bubbles of ionized hydrogen around them that expand until their ionizing photons are consumed by the neutral IGM. The larger the bubbles are, the faster reionization happened.

- Protons and electrons have intrinsic magnetic dipole moments to their spins which their interactions causes a slight increase in the energy when the spins are parallel and a decrease when the spins are anti-parallel. This transtion emits a photon at $\lambda = 21$ cm or $\nu = 1420.4057$ MHz. This transition is highly forbidden because the probability for this transition is given by Einstein coefficient $A_{10} = 2.85 \times 10^{-15}$ which corresponds to a lifetime of $\sim 10^7$ years for a spontanous emission.

- The spin temperature, defined by the relative number of electrons in ground and the triplet state, is given by:

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-T_\star/T_s}, \tag{1}$$

  where g_1 and g_0 are statistical weights (here 3 and 1, respectively) and $T_\star = 0.068$ K (since $k_B T_\star = h\nu_{21}$).

- How temperatures including T_s, T_k and T_{CMB} are related in different eras is as follows:

  1. $z > 200$: The temperatures T_{CMB}, T_k and T_s are in equilibrium due to Thomson scattering of residual free electrons and since $T_{CMB} = T_s$, we expect to see no 21-cm signal.
  2. $30 < z < 200$: gas cools adiabatically with temperature falling as $(1+z)^2$ which is faster than the $(1+z)$ factor for the CMB. T_s and T_k are still coupled due to high mean density, so we expect to see 21-cm absorption lines against the CMB.
  3. $20 < z < 30$: T_s and T_k are no longer coupled, but the Lyα photons from the first luminous objects may induce local coupling of T_s and T_k. T_s approached T_{CMB} as well, so we expect to see regions with no 21-cm emission and regions with some 21-cm absorption lines.
  4. $6 < z < 20$: The IGM is being warmed by the Xrays from the galaxies and BH such that T_k is globally larger than T_{CMB}. In this epoch, objects are changing linear evolution to a bubble-dominated era of ionized hydrogen.

- Differential brightness temperature is the difference between the CMB and the brightness temperature, which is given by:

$$\delta T_b \quad \equiv \quad T_B - T_{CMB,0} = \frac{T_s - T_{CMB}}{1+z}\tau = \frac{3c^3 n_{HI} A_{10} T_\star}{32\pi\nu_{21}^3 H(z)(1+z)}\left(1 - \frac{T_{CMB}}{T_s}\right), \tag{2}$$

In the case $T_s \gg T_{CMB}$, $\frac{T_{CMB}}{T_s}$ goes to 0 and therefore, the differential brightness temperature becomes independent of the spin temperature and only depends on the n_{HI}, the neutra hydrogen fraction.

- τ in equation (2) is the optical depth of a cloud of hydrogen and is given by:

$$\tau_{\nu_0} = \frac{3hc^3 A_{10}}{32\pi k_B T_s \nu_0^2} \frac{x_{HI} n_H}{(1+z)(dv_\parallel/dr_\parallel)}, \tag{3}$$

where $dv_\parallel/dr_\parallel$ is the gradient of the proper motion velocity along the line of sight and $N_{HI} = x_{HI} n_H$ is the column density of the HI.

- The HI signal produced by the EoR is very difficult to detect because it is weak ($\sim$ mK), relatively broad in frequency, redshifted to low frequencies and lies behind much brighter foreground of extragalactic radio sources.

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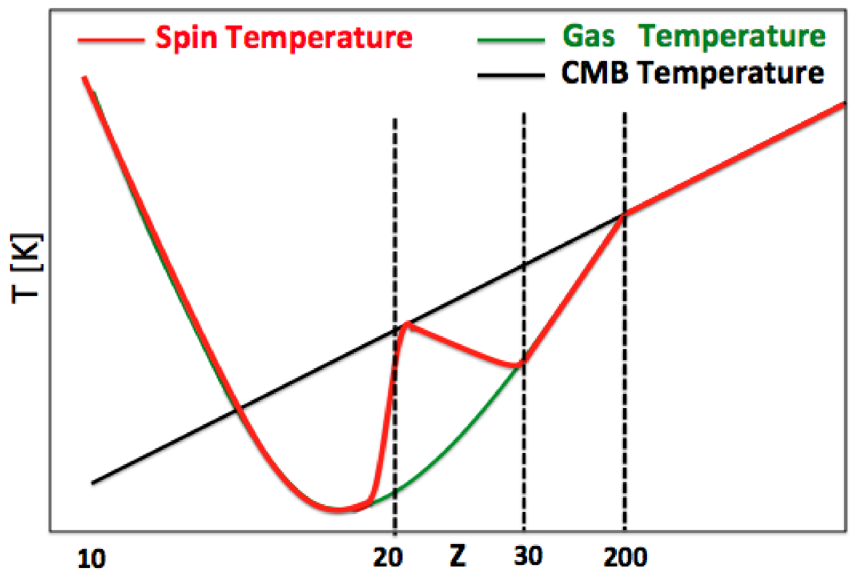

Fig. 1.— Evolution of temperatures, T_s, T_k, T_{CMB}. At redshift above 200, all three temperatures are coupled and we get no 21-cm signal. at redshifts between 30 and 200, the spin temperature is coupled to the kinetic temperature and we see absorption lines of 21-cm. For redshifts 20 to 30, the spin temperature is again coupled to the CMB temperature and for redshifts between 6 and 20, the spin temperature is coupled to the gas temperature once again.