21 cm Cosmology in the Epoch of Reionization

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I. Why is 21 cm 'the richest of all cosmological data sets'?

The 21 cm line of Hydrogen is caused by the hyperfine structure. When both the electron and the proton have the same spin, they have slightly higher energy than when their spins are opposite [1]. This transition in the 1s orbital has $\Delta E = 5.9 \times 10^{-6}$ eV and emits a photon of wavelength of 21.106 cm with frequency $\nu_{21} = 1420.4057$ MHz [2].

Hydrogen being the most common element, the 21 cm line is a great tool to infer the properties of the Universe. To see the usefulness of the 21 cm line, we must understand how CMB energy is transferred to neutral Hydrogen so that 21 cm photons are emitted. We thus begin with the most basic form of the radiative transfer equation along the line of sight (LOS) whose path is parametrized by s:

$$\frac{dI_\nu}{ds} = -I_\nu \alpha_\nu + j_\nu, \tag{1}$$

where I_ν is the specific intensity, α_ν and j_ν are the absorption and emission coefficients, respectively. Optical depth is usually defined as $\tau = \int dt\ \Gamma_t = \int ds\ c\Gamma_s$, where Γ is the scattering rate, and the subscript indicates whether it is per unit time or per unit distance. It tells us how many times on average a photon is expected to interact on its path from its source to us. In other words, a high optical depth at some frequency means that we expect photons at that frequency to scatter a lot on average and thus we most likely will not be able to observe them. We can now rewrite the radiative transfer equation in terms of the optical depth τ_ν:

$$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + \frac{j_\nu}{\alpha_\nu} \tag{2}$$

We then have that if $dI_\nu/d\tau_\nu = 0$ then the amount of absorption is equal to the amount of emission and thus no signal is observed. If we suppose that j_ν/α_ν is constant over the LOS i.e. is not a function of s, and that $\tau_\nu \ll 1$, then the solution to this differential equation would be:

$$I_\nu(s) - I_\nu(0) \simeq \big(j_\nu/\alpha_\nu - I_\nu(0)\big)\tau_\nu(s) \tag{3}$$

Usually, at $s = 0$, we have the CMB. This equation tells us that emission occurs when $I_\nu(s) > I_\nu(0) = I_{\nu,CMB}$, and similarly, absorption against the CMB when, $I_\nu(s) < I_{\nu,CMB}$. Recall that the specific intensity $I_\nu(\nu, T_B)$ is the blackbody distribution as a function of frequency ν and brightness temperature T_B. Since photon frequencies ν are much smaller than the CMB blackbody peak frequency, we can work in the Rayleigh-Jeans limit, where

$$I_\nu \simeq 2k_B T_B \nu^2/c^2, \tag{4}$$

where k_B is the Boltzmann constant. Plugging this expression into the previous equation yields

$$\delta T_B \equiv T_B(s) - T_{CMB} = \big(T_S - T_B(s)\big)\tau_\nu(s), \tag{5}$$

where we define the observable quantity δT_B known as intensity and $T_B(0) = T_{CMB}$. We also introduce the spin temperature T_S, also known as excitation temperature. T_S is the temperature of the HI cloud in the intergalactic medium (IGM) along the LOS. This equation yields that absorption of 21 cm signal against the CMB would occur when $T_S < T_{CMB}$, emission when $T_S > T_{CMB}$ and no signal when $T_S = T_{CMB}$. This shows the great importance of understanding the spin temperature in order to understand the 21 cm signal in great detail. We will not provide any more details about the spin temperature here, but a great reference is [1]. The final form of the observed intensity δT_B of the 21 cm line is:

$$\delta T_B \simeq \frac{T_S - T_{CMB}}{1+z}\tau \tag{6}$$

$$\simeq 7(1+\delta)x_{HI}\Big(1 - \frac{T_{CMB}}{T_S}\Big)\sqrt{1+z}\ \text{mK}, \tag{7}$$

where x_{HI} is the fraction of neutral hydrogen, and δ is the is the fractional overdensity of baryons with $(1+\delta) \propto \frac{\tau_\nu^2 T_S^2}{(1+z)^3}$. We can now begin to understand why 21 cm is the 'richest of all cosmological data sets' [3]. Looking at Figure 1 below, we see the intensity of the 21 cm signal as a function of observed frequency/redshift.

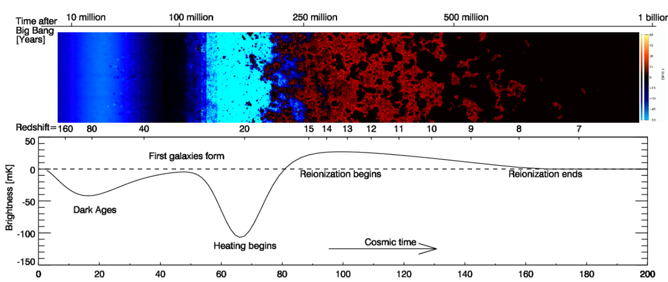

Fig. 1. **Lower panel**: 21 cm signal intensity/brightness temperature as a function of redshift/observed frequency. **Upper panel**: Colour represents intensity in mK as a function of redshift. [1]

- $z > 200$: High gas density. $T_S = T_{CMB}$ and therefore we will not observe any 21 cm signal.

- $30 \lesssim z < 200$: Gas cools adiabatically. The density is still relatively high. The temperature drops as $(1+z)^2$, in comparison to the CMB temperature which drops as $(1+z)$. $T_S < T_{CMB}$ therefore the 21 cm signal is seen in absorption against the CMB backlight.
- $20 \lesssim z \lesssim 30$: Photons from the first luminous objects induce 21 cm absorption in some regions.
- $6 \lesssim z \lesssim 20$: The IGM is heated up by the first galaxies and black holes, which leads to $T_S > T_{CMB}$ and thus 21 cm emission. These new formations are also reionizing the Universe.

II. Line Intensity Mapping

The large scale structure (LSS) is commonly studied via galaxy redshift surveys, which require individual galaxies to be resolved. This requires higher sensitivity with increasing redshift and is thus becoming more difficult. Line intensity mapping (LIM) is a recently developed technique where the integrated emission from sources across different redshifts is detected. It has the power to perform precision cosmology all without detecting individual sources. Integrating such sky maps at different frequencies allows depth perception and a 3-D map of LSS can be made [4]. In Figure 2 below, we see simulated intensity maps at three different values of redshift, namely $z = 12, 9$ and 7, from left to right. The LIM data

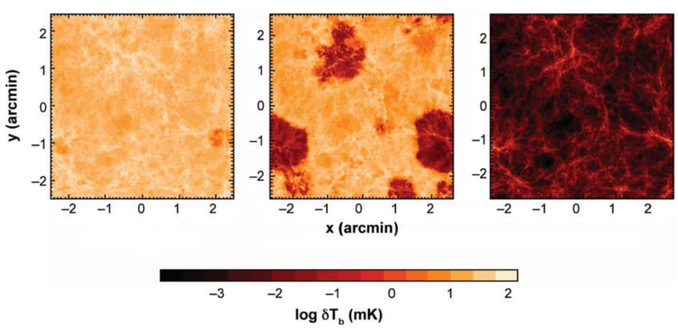

Fig. 2. Simulated HI brightness temperature. **Left**: $z = 12$. The whitest patches are the densest and will eventually turn into stars and quasars. We can see some light brown patches meaning that star and quasar formation already began and ionization already started. Bubbles of ionized gas begin to form. **Middle**:$z = 9$. More such bubbles form, expand and eventually merge. **Right**: $z = 7$. Very little neutral hydrogen left. What HI remains is concentrated in galaxies. [7], [5]

set will allow us to answer many questions concerning the nature of dark matter, and will allow for tests of gravity to be preformed [6].

III. Challenges

Recall that the intensity of the 21 cm signal we calculated is in the order of mK, which means that the data needs to be very well understood, with all other sources of signal well accounted for.

A. Foregrounds

Recall that the observed intensity due to 21 cm is of order mK. In Figure 3, the order of magnitude of the temperature is

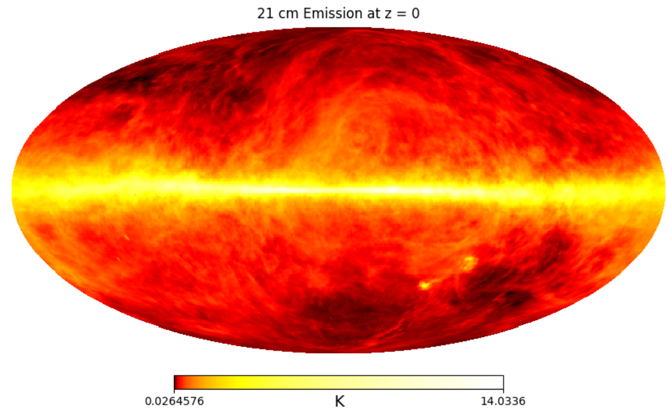

Fig. 3. All sky emission at $z = 0$ in galactic coordinates. Roughly 90% of this signal is due to the Milky Way (notice the Milky Way plane in yellow), and roughly 10% of this signal is made up of bright sources such as other galaxies and stars. [8] from LAMBDA.

of order K. Over 99% of the signal in this figure is due to our Milky Way and other galaxies. 21 cm signal is only 10^{-4} times the foreground emission signal. The key point to detecting 21 cm, then, is how well we can subtract these foregrounds. This can be very difficult for the instrument: foregrounds and instrument calibration are coupled, in the sense that instrumental response corrupts foreground properties. Fortunately, these foregrounds have a smooth spectrum in comparison to 21 cm, which means that a smooth powerlaw-like model can be used to account for them, among other methods, such as spectral cross-correlation.

B. Ionosphere

The index of refraction of ionized plasma fluctuates on patches of size $\sim 10^{o}$. These fluctuations induce a phase fluctuation in the data. If small sky area observations are made, of the size of that patch or less, this fluctuation can be easily accounted for via standard calibration. However, this becomes a serious issue for wide field observations, which would include multiple patches with the same phase error, a more complicated method to properly calibrate the instrument is required.

C. Interference

The low frequency range across which 21 cm signal is observed (7-200 MHz) is not protected, meaning that astronomers share it with TV and radio broadcasts, among others. Often, telescopes are built in remote areas to avoid these signals as much as possible. But no matter how remote, there will always be interference on Earth. This is the motivation behind the LUNAR project, that aims to build its detectors on the far side of the moon (LUDAR [9]).

IV. Conclusion

21 cm cosmology is a rapidly developing and exciting field with huge promise. Currently, there are already many ongoing projects with aim to observe 21 cm such as the Long

Wavelength Array (LWA[1]), Hydrogen Epoch of Reionization Array (HERA[2]), Square Kilometer Array (SKA[3]), Murchison Widefield Array (MWA[4]), and many more!

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