Neutral hydrogen at high redshift: probing structure formation

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Abstract. Large inhomogeneities in neutral hydrogen in the universe can be detected at redshifts \( z \leq 10 \) using the redshifted 21cm line emission from atomic hydrogen. This paper reviews the expected evolution of neutral hydrogen and presents estimates for future surveys of HI at \( z \approx 3 \). We also discuss the possibility of detecting neutral hydrogen at higher redshifts.

1. Introduction

It is generally believed that large scale structures like galaxies and clusters of galaxies formed from small initial inhomogeneities via gravitational collapse. This means that neutral hydrogen was distributed homogeneously at very high redshifts \( (z \gg 20) \). After recombination, the fraction of neutral hydrogen in molecular form increases with decreasing redshift (Tegmark et al. 1997). This leads to formation of clusters of stars \( (M_{cl} \approx 10^6 M_\odot, z \approx 20) \). UV radiation from these clusters dissociates \( \text{H}_2 \) molecules (Haiman, Rees and Loeb 1997) preventing formation of more star clusters via molecular cooling as the Jeans mass increases by about two orders of magnitude.

The Inter-Galactic Medium (IGM) is completely ionized at \( z \leq 5 \) (Giallongo et al. 1994) and neutral hydrogen exists only in dense clumps where the large column density prevents ionizing radiation from penetrating the inner regions.

The Universe is reionized between the formation of first star clusters at \( z \approx 20 \) and the highest redshift quasars at \( z \approx 5 \). The epoch of reionization, and the distribution of sources of ionizing radiation, leave their imprint on the distribution of neutral and ionized gases. The distribution of hydrogen is largely homogeneous before a significant fraction of the volume is ionized. In the intermediate regime, when the Universe is partially ionized, neutral hydrogen exists in two phases: A warm phase that has been heated \( (T_{\text{spin}} \gg T_{\text{cmb}}) \) by radiation from ionizing sources. This phase surrounds the ionized regions. The cold phase of neutral hydrogen \( (T_{\text{spin}} \approx T_{\text{cmb}}) \) can be found in regions far away from sources of ionizing radiation. The warm phase can be observed in redshifted 21cm emission whereas no such radiation is expected from the ionized or the cold phases of gas. This patchiness will certainly exist at observable angular scales if quasars are the main source of ionizing radiation (Madau, Meiksin and Rees 1997).
After reionization of the IGM, neutral hydrogen distribution traces the distribution of collapsed dark matter halos with circular velocity $v_c > 50\,\text{km}\,\text{s}^{-1}$ (Thoul and Weinberg 1996). In this regime, it is possible to estimate the mass in neutral hydrogen in clumps from models of galaxy formation. Proto-clusters, or large groups of such halos may be observed in the redshifted 21cm line emitted by the neutral hydrogen in these structures.

Thus there are two regimes in which neutral hydrogen can be observed at high redshifts. Early epochs, when the Universe is being ionized and patchiness in the ionization and temperature makes a part of the universe visible in the redshifted 21cm band, and, late epochs when neutral hydrogen in self gravitating dense clumps is the main source of signal. We will discuss the prospects of observing redshifted 21cm line from post-reionization epochs first and then discuss some aspects of the early, pre-reionization epochs.

2. Neutral Hydrogen after IGM is Reionized

After reionization of IGM is complete, neutral hydrogen survives only in high density, radiatively cooled objects (Weinberg et al. 1996). Such systems are expected to trace the distribution of galaxies and can exist only in regions where the density of dark matter is well above average. Thus the large scale distribution of neutral hydrogen, and the distribution of dense halos of dark matter is the same.

Subramanian and Padmanabhan (1993) computed the expected flux from proto-clusters at $z \simeq 3$ for some models of structure formation. They used the Press-Schechter formalism (Press and Schechter, 1975) to compute the expected number density of proto-clusters in the CDM and HDM models. This estimate was a pilot study for the Giant Meter-wave Radio Telescope (GMRT) presently being constructed in India (Swarup, 1984). Modeling was refined in a later paper (Kumar, Padmanabhan and Subramanian, 1995) where they computed line profiles assuming the proto-clusters to be spherical perturbations composed of virialized clumps of smaller masses. These studies suggest that it should be possible to detect proto-clusters in the COBE normalized standard CDM model using the GMRT with 10 to 20 hours of observations. However, structures that are expected to contribute strong signal are very rare peaks in the density field and are expected to occur in about every fifth field of view.

Some authors have studied the distribution of neutral hydrogen at high redshifts using simulations that include gas dynamics, ionization and other astrophysical processes. Most of these studies focus on small scale variations in the distribution of neutral hydrogen. [e.g. see Weinberg et al. (1996)] However, the synthesized beam, at frequencies suited for detecting redshifted 21cm line from $z \geq 3$, for most telescopes available at present includes a large comoving volume and so the details of physical processes operating at small scales can be ignored to a large extent. The sensitivity of these telescopes is also not sufficient to probe small scale structure. Thus we can ignore the differences in distribu-

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1 The GMRT will be able to probe the redshifted 21cm line from three epochs centered at $z = 3.34, 5.1$ and 8.5.
tion of baryons and dark matter at small scales. Further, as we are interested in the neutral fraction at a given epoch, we can choose to ignore the physical processes responsible for its evolution. This simplifies the problem to a large extent and we can get meaningful estimates of the signal strength without a detailed treatment of baryons and astrophysical processes.

2.1. Modeling

Observations of the damped Lyman-α absorption systems (DLAS), believed to be progenitors of present day galaxies, suggest that a large fraction of mass in these is in form of HI (Wolfe et al. 1995). Observations also show that the spin temperature of gas in DLAS, the relevant quantity for the 21cm radiation, is much higher than the temperature of the background radiation at this epoch. Large HI fraction can also be inferred indirectly from the tentative estimates of star formation history (Connolly et al. 1997). These estimates suggest that the peak of star formation activity is around \( z \approx 2 \), thus a large fraction of the gas may be in the neutral form at redshifts higher than this.

We can summarize a set of reasonable assumptions that can be used to estimate the distribution of neutral hydrogen at high redshifts, and the expected signal in the redshifted 21cm line.

- Neutral hydrogen exists only in highly over dense regions. Thus the distribution of neutral hydrogen is the same as the distribution of dense halos.
- Neutral hydrogen shares the velocity field of the dark matter distribution, and the velocity dispersion of halos in which it resides.
- Neutral fraction in these regions is expected to be high at \( z \geq 2 \), i.e. before the star formation activity reached its peak level.

An additional fact that is of considerable importance is that the primary beam of most telescopes that have, or will have, the sensitivity to detect neutral hydrogen at high redshift, contains a very large comoving volume. For example, the primary beam for the GMRT includes a comoving volume of \( \approx 10^6 \, h^{-3} \text{Mpc}^3 \). Therefore, probability of finding a rare peak, like proto-clusters of mass \( \approx 10^{14} M_\odot \) is reasonably high. Any implementation of the method outlined above must treat these rare objects in a fair manner as these will be the first objects to be detected in redshifted 21cm emission line.

2.2. Results

The spatial distribution of neutral hydrogen, when combined with the velocity field, gives the redshift space distribution. This can then be used to determine the expected flux in a fairly straightforward manner. If the spin temperature is much greater than the temperature of the CMBR then the spin temperature drops out of the expression for the emitted energy, which then is proportional

\[ \text{This is taken into account by using a simulation volume that is comparable to the volume enclosed in a primary beam of the GMRT.} \]
to the mass of neutral hydrogen. The observed flux can be written in terms of the mass in atomic hydrogen and the velocity width of this distribution.

\[ S_\nu \simeq 220 \mu Jy \left( \frac{M_{HI}}{10^{13} M_\odot} \right) \left( 1 \text{MHz} \frac{1}{\Delta \nu_0} \right) \left( \frac{D_L(z = 3.34, h = 0.5, \Omega_0 = 1, \Lambda = 0)}{D_L(z)} \right)^2 \]  

(1)

Here \( M_{HI} \) is the mass in neutral hydrogen in the atomic form, \( \Delta \nu_0 \) is the spread in frequency space in the observer’s frame and corresponds to a rest frame velocity width of \( v_{\text{disp}} \approx 1000 \text{ km s}^{-1} \) at redshift \( z = 3.34 \) and \( D_L \) is the luminosity distance. For reference, we have used the luminosity distance for an Einstein-de Sitter Universe with \( h = 0.5 \) at \( z = 3.34 \). We can write for \( M_{HI} \),

\[ M_{HI} = M_{total} \frac{f_{\text{neutral}}}{\Omega_0} = 0.025 M_{total} \left( \frac{f_{\text{neutral}}}{0.5} \right) \left( \frac{\Omega_b}{0.05} \right) \left( \frac{\Omega_0}{1} \right) \]  

(2)

We can compare the expression for flux with the sensitivity of the GMRT.

\[ \text{rms noise} = 44 \mu Jy \left( \frac{T_s}{110 K} \right) \left( \frac{1 \text{MHz}}{\Delta \nu} \right)^{1/2} \left( \frac{100 \text{hrs}}{\tau} \right)^{1/2} \]

\[ = 100 \mu Jy \left( \frac{T_s}{250 K} \right) \left( \frac{1 \text{MHz}}{\Delta \nu} \right)^{1/2} \left( \frac{100 \text{hrs}}{\tau} \right)^{1/2} \]  

(3)

Thus it should be possible to detect a proto-condensate of mass \( M_{HI} = 10^{13} M_\odot \) or greater with about 100 hours of observations. In the context of existing constraints (Wieringa, de Bruyn and Katgert 1992), GMRT will be able to probe mass scales that are about an order of magnitude smaller than those accessible to previous surveys at redshift \( z \approx 3 \). The square kilometer array being planned (Braun 1996) is expected to have the sensitivity to detect clumps of neutral hydrogen above \( 10^9 M_\odot \).

Bagla, Nath and Padmanabhan (1997) studied some models of structure formation and generated radio maps from N-Body simulations of dark matter using the assumptions outlined above. The highest peaks in most models studied there have a flux around 150 \( \mu Jy \) for the redshift window \( z = 3.34 \). Figure 1 shows a radio map constructed from a simulation of the standard CDM model. The power spectrum was normalized to match the abundance of clusters at the present epoch, i.e. \( \sigma_8 = 0.6 \). The map shows angular distribution of flux from a region of width 0.125kHz at \( z = 3.34 \). Pixels are 3.2' wide, corresponding to about 3h^{-1}Mpc (comoving). The contour levels correspond to a signal of 80, 60, 40 and 20 \( \mu Jy \). A density threshold of \( 4 \bar{\rho} \) was used in constructing this map. The highest peak encountered in this simulation had a flux of 115 \( \mu Jy \) and a FWHM of about 1MHz. The contour for half signal enclosed three pixels. We used a neutral fraction \( f_N = 0.5 \).

If the assumption of complete reionization of the IGM is valid at \( z \approx 5 \) then the expected signal, for the same models is about 200 \( \mu Jy \), which can also be observed with 100 – 200 hours of observations.

\[ ^3 \text{These numbers are for the central square which has 12 antennas spread in a region of 1sq km.} \]
Figure 1. This figure shows a sample radio map ($z = 3.34$ from a simulation of the standard CDM model. Angular size of each pixel is $3.2'$, corresponding to about $3h^{-1}$Mpc (comoving), and the bandwidth of this image is 125kHz. The contour levels correspond to a signal of 80, 60, 40 and 20 $\mu$Jy. A density threshold of $4\bar{\rho}$ was used in constructing this map.
In general, the expected signal for a fixed neutral fraction depends mainly on the amplitude of fluctuations at the cluster scale. The angular size of typical proto-condensates depends on the slope of the power spectrum at cluster scales. Power spectra with more power at smaller scales give rise to more concentrated proto-condensates.

Thus a direct detection of proto-condensates, at $z \simeq 3$ and $z \simeq 5$ should be possible with observations of about $100-200$ hrs if we search for a spectral line in emission. Another possible method is to look for variations in rms flux received from different directions. This method is quicker, but may not be practical if confusion due to fainter sources dominates at these angular scales. Using high resolution imaging to reduce the contribution of confusion may make this method feasible for detecting neutral hydrogen. This may be possible, in the case of the GMRT, if the full array is used for collecting data. Then the longer baselines can be used to remove discrete sources. This method will also reduce the integration time required by a significant amount as all 30 antennas can be used instead of the 12 in the central square. As an aside, we would like to point out that it will be possible to detect objects in the continuum emission down to a few tens of $\mu$Jy, making any observed field the most well studied one at low frequencies. These sources will include faint AGNs and star forming galaxies. Multi-frequency observations of the same field will provide considerable wealth of information about these sources, making it a worthwhile project for more than one reason.

Recent observations of Lyman break galaxies at $z \approx 3$ have revealed large spikes in their redshift space distribution (Steidel et al. 1998). The estimated mass contained in these spikes is comparable to $10^{15} M_\odot$ and hence these are natural targets for searches of neutral hydrogen at $z \approx 3$. These observations also suggest that the probability of finding such spikes at high redshifts is large.

3. Neutral Hydrogen before reionization of IGM is complete

Hydrogen in the Universe exists in three phases at epochs before reionization is complete. The ionized phase in and around dense clumps where sources of ionizing radiation are present: young stars, and/or, quasars. The warm phase that is expected to envelope the ionized phase, these regions have neutral hydrogen with $T_{\text{spin}} \gg T_{\text{cmb}}$. Rest of the Universe contains cold gas with $T_{\text{spin}} \approx T_{\text{cmb}}$. It is possible, in principle, to observe the warm phase in red shifted 21cm line (Madau, Meiksin and Rees 1997). These will appear as patchy shells around (invisible) sources of ionizing radiation. The typical separation of shell centers can be used as an indicator of the number density of ionizing sources. The separation will be large if the sources are rare objects like quasars. However, it will be small if most of the ionizing radiation comes from stars. It is expected that these early structures will cluster strongly (Bagla 1997) and hence the typical separation between shell centers will be many times larger than $n^{-1/3}$ where $n$ is the number density of sources.

Observability of patchiness at high redshifts require observations at very low frequencies, e.g., 160MHz for $z \approx 8$ and 70MHz for $z \approx 20$. At these low frequencies, and at the very low flux levels, the ionosphere and galactic emission
are the main sources of noise. In the near future, it will be possible to attempt observations at 150MHz using the GMRT.

4. Summary

Detection of proto-clusters at $z \approx 3$ should be possible in near future. This requires integration of about 100hrs with the existing and upcoming telescopes, the numbers presented here were computed specifically for the GMRT.

If interferometric observations can be carried out at 233MHz for the low flux levels expected from proto-clusters then it may be possible to detect proto-clusters at $z \approx 5$ as well.

Patchiness in the pre-reionization stage may be observed using the 21cm tomography (Madau, Meiksin and Rees 1997) at $z \approx 8$ if low flux levels can be observed at 150MHz. This may be possible, if at all, only during solar minimum when the ionosphere is relatively stable.

Any search for neutral hydrogen at high redshifts will have spin-offs like observations of star burst galaxies and faint AGNs to very low flux levels.

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