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H I 21-cm observations of cosmic re-ionization

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Abstract. I review the potential for observing cosmic re-ionization using the H I 21 cm line.

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1. Introduction

Cosmic re-ionization corresponds to the transition from a fully neutral intergalactic medium (IGM) to an (almost) fully ionized IGM caused by the UV radiation from the first luminous objects. Re-ionization is a key benchmark in cosmic structure formation, indicating the formation of the first luminous objects. Re-ionization, and the preceding 'dark ages', remain the last of the major phases of cosmic evolution left to explore. Recent observations of the Gunn-Peterson effect, i.e., Ly-α absorption by the neutral IGM, toward the most distant QSOs ($z \simeq 6$), and the large scale polarization of the CMB, have set the first constraints on the epoch of re-ionization. These data, coupled with the study of high-z galaxy populations and other observations, suggest that re-ionization was a complex process, with significant variance in both space and time, starting around $z \simeq 10$, with the last vestiges of the neutral IGM being etched away by $z \simeq 6$ (Fan *et al.* 2006; Ciardi & Ferrara 2005).

The most direct and incisive means of studying cosmic re-ionization is through the 21 cm line of neutral hydrogen (Furlanetto *et al.* 2006). Many programs have been initiated to study the H I 21 cm signal from cosmic re-ionization, including the MWA†, LOFAR‡, PAPER¶, and eventually the SKA‖. Fan *et al.* (2006) and Furlanetto *et al.* (2006) present detailed discussions of the observational challenges.

2. Expected H I 21-cm signals from cosmic re-ionization

The study of H I 21-cm emission from cosmic re-ionization entails the study of large scale structure (LSS), meaning H I masses $> 10^{12}$ M$_\odot$. During this epoch the entire IGM may be neutral, and the LSS in question is not simply mass clustering, but involves a combination of structure in cosmic density, neutral fraction, and H I excitation temperature. Hence, H I 21-cm studies are potentially the 'richest of all cosmological data sets' (Barkana & Loeb 2005).

2.1. *Global signal*

Figure 1 (left panel) shows the latest predictions of the global (all sky) increase in the background temperature due to the H I 21-cm line from the neutral IGM (Gnedin &

† http://web.haystack.mit.edu/arrays/MWA/LFD/
‡ http://www.lofar.org/
¶ D. Backer, in prep
‖ http://www.skatelescope.org/

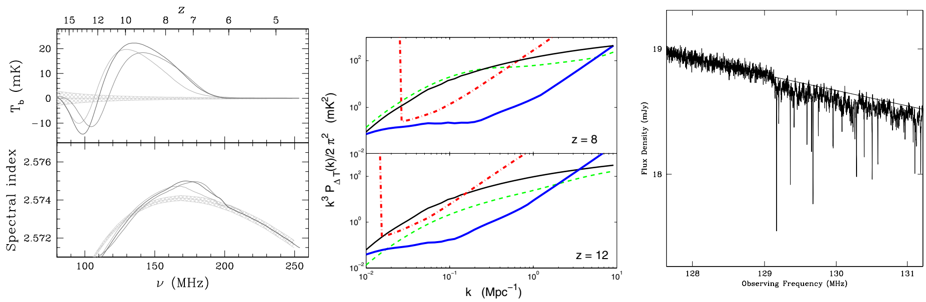

Figure 1. *Left*: Global (all sky) H I signal from re-ionization (Gnedin & Shaver 2003. The shaded region shows the expected thermal noise in a carefully controlled experiment. *Center*: Predicted H I 21-cm brightness temperature power spectrum (in log bins) at redshifts 8 and 12 (Mcquinn *et al.* 2006). The thin black line shows the signal when density fluctuations dominate. The dashed green line shows the predicted signal for $\bar{x}_i = 0.2$ at $z = 12$, and $\bar{x}_i = 0.6$ at $z = 8$, in the Furlanetto *et al.* (2004) semi-analytic model. The thick blue line shows the SKA sensitivity in 1000 hr. The thick red dot-dash show the sensitivity of the pathfinder experiment LOFAR. The cutoff at low k is set by the primary beam. *Right*: The simulated SKA spectrum of a radio continuum source at $z = 10$ (Carilli *et al.* 2002). The straight line is the intrinsic power law (synchrotron) spectrum of the source. The noise curve shows the effect of the 21-cm line in the neutral IGM, including noise expected for the SKA in a 100 hr integration.

Shaver 2003). The predicted H I signal peaks at roughly 20 mK above the foreground at $z \simeq 10$. At higher redshift, prior to IGM warming, but allowing for Ly-α emission from the first luminous objects, the H I is seen in absorption against the CMB. Since this is an all-sky signal, the sensitivity of the experiment is independent of telescope collecting area, and the experiment can be done using small area telescopes at low frequency, with very well controlled frequency response (Subrahmanyan *et al.* 2005, in prep.). Note that the line signal is only $\sim 10^{-4}$ that of the mean foreground continuum emission at ~ 150 MHz.

2.2. *Power spectra*

Figure 1 (middle panel) shows the predicted power spectrum of spatial fluctuations in the sky brightness temperature due to the H I 21-cm line (Mcquinn *et al.* 2006). For power spectral analyses the sensitivity is greatly enhanced relative to direct imaging due to the fact that the Universe is isotropic, and hence one can average the measurements in annuli in the Fourier (u-v) domain, i.e., the statistics of fluctuations along an annulus in the u-v plane are equivalent. Moreover, unlike the CMB, H I line studies provide spatial and redshift information, and hence the power spectral analysis can be performed in three dimensions. The rms fluctuations at $z = 10$ peak at about 10 mK rms on scales $\ell \simeq 5000$.

2.3. *Absorption toward discrete radio sources*

An alternative to emission studies is the possibility of studying smaller scale structure in the neutral IGM by looking for H I 21-cm absorption toward the first radio-loud objects (AGN, star forming galaxies, GRBs, Carilli *et al.* 2002). Figure 1 (right panel) shows the predicted H I 21-cm absorption signal toward a high-redshift radio source due to the 'cosmic web' prior to re-ionization, based on numerical simulations. For a source at $z = 10$, these simulations predict an average optical depth due to 21-cm absorption of about 1 %, corresponding to the 'radio Gunn-Peterson effect', and about five narrow (few km s^{-1}) absorption lines per MHz with optical depths of a few to 10 %. These latter lines are equivalent to the Ly-α forest seen after re-ionization. Furlanetto & Loeb (2002) predict a similar H I 21-cm absorption line density due to gas in minihalos as that expected for the 21-cm forest.

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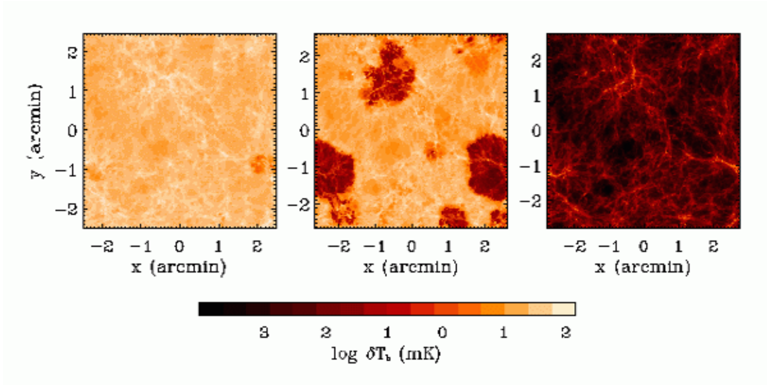

Figure 2. The simulated H I 21-cm brightness temperature distribution during re-ionization at $z = 12$, 9, and 7 (left to right, Zaldariagga *et al.* 2004).

2.4. *Tomography*

Figure 2 shows the expected evolution of the H I 21 cm signal during re-ionization based on numerical simulations (Zaldariagga *et al.* 2004). In this simulation, the H II regions caused by galaxy formation are seen in the redshift range $z \simeq 8$ to 10, reaching scales up to $2'$ (frequency widths ~ 0.3 MHz or physical size ~ 0.5 Mpc). These regions have (negative) brightness temperatures up to 20 mK relative to the mean H I signal. This corresponds to $5\,\mu$Jy beam^{-1} in a $2'$ beam at 140 MHz. Only the full SKA will able to image such structures.

2.5. *Cosmic Strømgren spheres*

While direct detection of the typical structure of H I and H II regions may be out of reach of the near-term EoR 21-cm telescopes, there is a chance that even this first generation of telescopes will be able to detect the rare, very large scale H II regions associated with luminous quasars near the end of re-ionization. The expected signal is $\sim 20\,\mathrm{mK} \times x_{\mathrm{HI}}$ on a scale $\sim 10'$to $15'$, with a line width of ~ 1 to 2 MHz (Wyithe *et al.* 2005). This corresponds to $0.5 \times x_{\mathrm{HI}}$ mJy beam^{-1}, for a $15'$ beam at $z \simeq 6$ to 7, where x_{HI} is the IGM neutral fraction.

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