Statistical Challenges in 21st Century Cosmology
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The impact of small absorbers, galactic neutral hydrogen & X-rays on 1-point statistics of the 21-cm line.

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Abstract. We discuss a selection of semi-numerical simulations of reionization whose analysis investigates the effect of small absorbing systems, neutral hydrogen within galaxies and the efficiency with which galaxies produce X-rays. We focus on the consequences for both observing the 21–cm 1-point statistics and their interpretation.

Keywords. intergalactic medium, galaxies: high-redshift, cosmology: theory

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1. Introduction

Reionization, the process in which the first galaxies ionized the otherwise neutral intergalactic medium (IGM), is one of the least well constrained epochs in the history of our universe. We appear to be observing the final phases of the process at $z \sim 7$ in analysis of the highest known quasar (Bolton *et al.* 2011) and an apparent drop in Lyman-alpha emitters (Ota *et al.* 2010); we also know from the cosmic microwave background (CMB) that the process of reionization was under way by $z \sim 11$ (Planck collaboration 2013). Beyond this we know very little, so it is essential that we understand the effects that the associated uncertainties have on the observables with which we hope to constrain reionization. The 21-cm brightness temperature is an extremely promising such quantity, this temperature describes the intensity of the 21-cm line, a hyperfine transition of neutral hydrogen (H I). The hope is that we can detect this signal with huge radio interferometers such as LOFAR, MWA and SKA to observe evolution in the distribution of hydrogen as we look to $z > 6.5$. Here we overview results of semi-numerical simulations of reionization that allow us to infer the effects on the brightness-temperature 1-point statistics due to: absorbing sinks, H I that remains in galaxies after their local IGM is ionized and the efficiency with which stars produce X-rays.

2. Overview

The 21-cm line is observed through the difference between the transition's brightness temperature and that of the CMB, δT_{b}. It can in principle be detected whenever the excitation/spin temperature (T_{s}) is decoupled from that of the CMB (T_{cmb}). The 21-cm brightness temperature is also sensitive to cosmology [$H(z)$, Ω_{m} , Ω_{b}], density contrast (δ), neutral fraction (x_{HI}) and peculiar velocities ($\mathrm{d}v_r/\mathrm{d}r$) according to Equation 2.1,

$$\delta T_{\mathrm{b}} \approx 27.\, \frac{T_{\mathrm{s}} - T_{\gamma}}{T_{\mathrm{s}}}\, x_{\mathrm{HI}}(1+\delta) \left[\frac{H(z)/(1+z)}{\mathrm{dv_r/dr}}\right] \left(\frac{1+z}{10}\,\frac{0.15}{\Omega_{\mathrm{m}} h^2}\right)^{1/2} \left(\frac{\Omega_{\mathrm{b}} h^2}{0.023}\right) \mathrm{mK}\,. \tag{2.1}$$

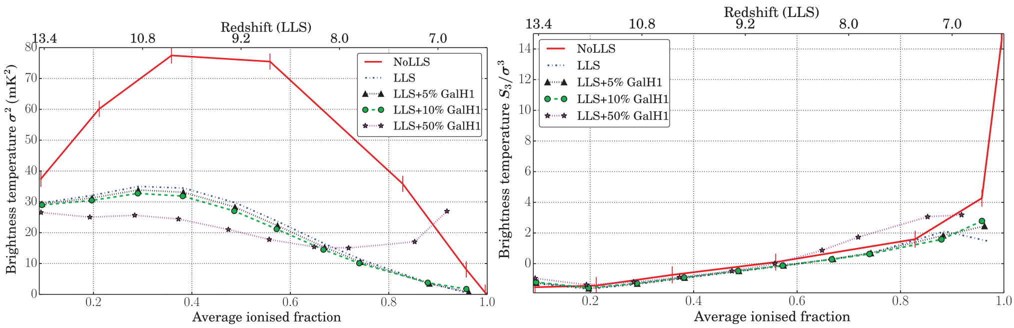

Figure 1. Absorbers & galactic H I: Variance (left) and skewness (right) of δT_b as a function of ionized fraction

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Neutral sinks & residual galactic hydrogen (Figure 1)

The effects that ionizing radiation from galaxies has on the IGM has been studied at great length using both numerical and semi-numerical methods; both agree that the collective effect of clustering galaxies will generate large ionized bubbles that exhibit a characteristic size which increases as reionization proceeds. Such simulations, including 21CMFAST (Mesinger *et al.* 2011) labelled as **NoLLS** in Figure 1, only consider homogeneous recombinations, yet we observe strongly absorbent, self-shielded and neutral Lyman-limit systems (**LLS**) at lower redshifts and expect such systems to exist during reionization.

The effect that these systems have on the progress of reionization and the power spectrum was considered by Sobacchi & Mesinger 2014. In this simulation, they use sub-grid physics based on fits to simulations (Miralda-Escude *et al.* 2013, Schaye 2001, Rahmati *et al.* 2013) to self-consistently model localised recombinations. Here we calculate the 1-point statistics of their full simulation (**LLS** in Figure 1) and also consider the impact of remnant galactic H I (**LLS + %GalHI** in Figure 1). The evolution of remnant galactic H I remains completely unconstrained during the final phases of reionization so we assume that a fixed percentage of galaxies (assumed to be well approximated by the extended Press-Schechter collapsed fraction) remains neutral and vary this percentage to understand its impact.

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X-ray efficiency of galaxies (Figure 2)

The spin (excitation) temperature of the 21-cm transition is sensitive to the efficiency with which the first stars produced X-ray radiation which effects the heating of the IGM and causes partial ionizations. Simulations of reionization often assume that the spin temperature has already saturated and so fluctuations in the spin temperature are ignored (**T_s saturated** in Figure 2). Furthermore, the moments of the 21-cm brightness temperature have not been examined in the presence of these fluctuations. We generate a suite of 21CMFAST simulations that model spin-temperature fluctuations. We vary the efficiency of X-ray production by an order of magnitude either side of a fiducial value of 2e57 X-ray photons per solar mass (**ξ_x = 2e57** in Figure 2).

3. Implications

Neutral sinks & residual galactic hydrogen (Figure 1): Including small self-shielded neutral absorbers reduces the variance of the 21-cm signal; the inclusion of galactic hydrogen

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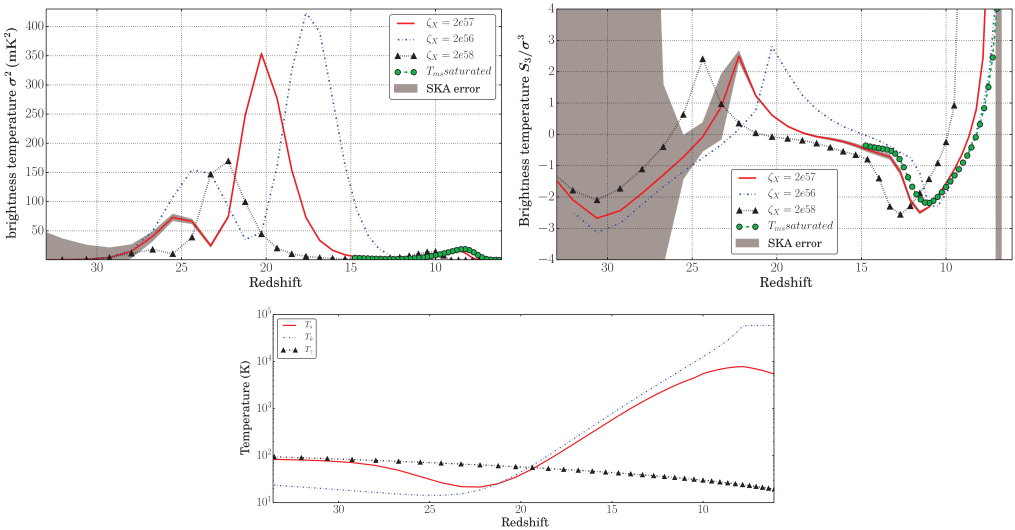

Figure 2. Spin temperature: Variance (top-left) and skewness (top-right) of $\delta T_{\rm b}$ as function of redshift; evolution of the spin temperature (red), kinetic temperature (blue dot-dashed) and CMB temperature (black dotted w/triangles) as a function of redshift for $\xi_{\rm x} = 2e57$ (bottom)

decreases its amplitude further as well as producing a kick up towards the end of reionization. The severity of these two effects is dependent on the percentage of galactic mass that is assigned to remain neutral and can potentially alter the qualitative nature of the variance's evolution. This effect will make the variance more challenging to detect and suppresses a turnover that if observed would provide a signature that reionization was at its mid point. Including LLS also wipes out a late-time signature of reionization in the skewness; this is replaced by a characteristic turnover which is in turn erased when even small amounts of galactic hydrogen remain in galaxies. The amplitude of the variance at the end or reionization can be used to constrain the amount of H I remaining in galaxies.

X-ray efficiency of galaxies (Figure 2): We see that the variance and skewness of the brightness temperature both exhibit distinct turnovers corresponding to the point at which $T_{\rm s}$ starts increasing with the gas kinetic temperature to which it is becoming coupled. This provides constraints on the timing of X-ray heating processes and the strength of this signature also increases with decreasing $\xi_{\rm x}$. We also see the variance is suppressed during reionization due to partial ionizations.

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