The impact of H I in galaxies on 21-cm intensity fluctuations during the reionization epoch

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ABSTRACT
We investigate the impact of neutral hydrogen (H I) in galaxies on the statistics of 21-cm fluctuations using seminumerical modelling. Following the reionization of hydrogen, the H I content of the Universe is dominated by damped absorption systems (DLAs), with a cosmic density in H I that is observed to be constant at a level equal to ∼2 per cent of the cosmic baryon density from z ∼ 1 to z ∼ 5. We show that extrapolation of this constant fraction into the reionization epoch results in a reduction in the amplitude of 21-cm fluctuations over a range of spatial scales. We further find that consideration of H I in galaxies/DLAs reduces the prominence of the H II region induced shoulder in the 21-cm power spectrum (PS), and hence modifies the scale dependence of 21-cm fluctuations. We also estimate the 21-cm–galaxy cross PS and show that the cross PS changes sign on scales corresponding to the H II regions. From consideration of the sensitivity for forthcoming low-frequency arrays, we find that the effects of H I in galaxies/DLAs on the statistics of 21-cm fluctuations will be significant with respect to the precision of a PS or cross PS measurement. In addition, since overdense regions are reionized first we demonstrate that the cross-correlation between galaxies and 21-cm emission changes sign at the end of the reionization era, providing an alternative avenue to pinpoint the end of reionization. The sum of our analysis indicates that the H I content of the galaxies that reionize the universe will need to be considered in detailed modelling of the 21-cm intensity PS in order to correctly interpret measurements from forthcoming low-frequency arrays.

Key words: galaxies: high-redshift – intergalactic medium – cosmology: theory – diffuse radiation – large-scale structure of Universe.

1 INTRODUCTION
The process of hydrogen reionization is thought to have started with ionized (H II) regions around the first galaxies, which later grew to surround groups of galaxies. Reionization completed once these H II regions overlapped and occupied most of the volume between galaxies. Much recent theoretical attention has focused on the power spectrum (PS) of 21-cm emission from neutral hydrogen (H I) during the reionization era (Furlanetto, Zaldarriaga & Hernquist 2004; Zaldarriaga, Furlanetto & Hernquist 2004; Bowman, Morales & Hewitt 2006; Morales, Bowman & Hewitt 2006). In particular, the ionization structure of the intergalactic medium (IGM) owing to ultraviolet (UV) emission associated with star formation has been studied in detail using analytic (Furlanetto et al. 2004; Barkana 2007), numerical (McQuinn et al. 2006; Iliev et al. 2008), and more recently, seminumerical models (Mesinger & Furlanetto 2007; Zahn et al. 2007; Geil & Wyithe 2008).

These studies describe a scenario in which very large H II regions form around clustered sources within overdense regions of the IGM. The formation of these H II regions has a significant effect on the shape of the 21-cm PS because information about the small-scale features in the density field is erased from the signal originating within the ionized regions. Conversely, the creation of large ionized regions imprints large-scale features on the distribution of 21-cm intensity. The sum of these effects is to move power from small to large scales, leaving a shoulder-shaped feature on the PS at the characteristic scale of the H II regions (Furlanetto et al. 2004). The detailed morphology of the ionization structure will therefore yield information about both the ionizing sources and the structure of absorbers in the IGM on small scales (McQuinn et al. 2006). As reionization leaves a strong imprint on the 21-cm PS, measuring the latter has become a key goal for learning about the reionization epoch (Furlanetto, Oh & Briggs 2006, and references therein). In addition, since reionization is driven by galaxy formation, whose

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statistics reflect those of the underlying density field, the detection of the redshifted 21-cm signal will not only probe the astrophysics of reionization, but also the matter PS during the epoch of reionization (McQuinn et al. 2006; Bowman, Morales & Hewitt 2007). Finally, it has been recognized that cross-correlating galaxy surveys with 21-cm maps could yield powerful new insights into the morphology of reionization, as well as eliminate some of the difficulties related to foreground removal (Furlanetto & Lidz 2007; Wyithe & Loeb 2007; Lidz et al. 2009). With these ideas as motivation, several experiments are currently under development that allow to detect the 21-cm signal during reionization, including the Low Frequency Array\(^1\) (LOFAR), the Murchison Widefield Array\(^2\) (MWA) and the Precision Array to Probe Epoch of Reionization\(^3\) (PAPER), and more ambitious designs are being planned such as the Square Kilometer Array\(^4\) (SKA).

Until now, only the component of H\(_i\) residing in the IGM has been considered in relation to forecasts of the statistical 21-cm signal. However, after the completion of reionization there is known to be a residual H\(_i\) fraction of a few per cent in high-density clumps which are believed to reside within galaxies (e.g. Prochaska, Herbert-Fort & Wolfe 2005). This high-density contribution to the H\(_i\) content of the Universe is also present during the reionization era (we refer to this high-density H\(_i\) as galactic H\(_i\) throughout the paper). Moreover, because galaxies at high redshift are biased relative to the density field, this galactic H\(_i\) contribution could provide a significant perturbation to the predicted statistics of 21-cm fluctuations.

Wyithe & Loeb (2007) have modelled the density-dependent reionization process using a semi-analytic model that incorporates the important physical processes associated with galaxy bias and radiative feedback. In agreement with numerical simulations (McQuinn et al. 2006; Iliev et al. 2008), this model demonstrates that galaxy bias leads to enhanced reionization in overdense regions. In this paper, we use a seminumerical extension of this model to explore the effect that the H\(_i\) content of the biased galactic sources of reionization would have on the fluctuations in redshifted 21-cm emission. We begin by summarizing the observed evolution of H\(_i\) density, and our related assumptions for the reionization era in Section 2. We next describe our seminumerical models, including the addition of galactic H\(_i\) in Section 3. The following sections describe results for the effect of galactic H\(_i\) on real and Fourier space 21-cm fluctuations (Section 4), and discuss prospects for their detection (Section 5). We conclude in Section 6. Throughout this paper, we adopt a concordance cosmology for a flat \(\Lambda\) cold dark matter universe, \((\Omega_m, \Omega_\Lambda, \Omega_b, h, \sigma_8, n) = (0.27, 0.73, 0.046, 0.7, 0.8, 1)\), consistent with the constraints from Komatsu et al. (2009). All distances are in comoving units unless stated otherwise.

2 THE H\(_i\) CONTENT OF HIGH REDSHIFT GALAXIES

Following the completion of reionization, around 2 per cent of the hydrogen content of the Universe is observed to be in H\(_i\) within galaxies. Moreover, this 2 per cent fraction is observed to be roughly constant from \(z \sim 1\) to \(z \sim 5\) (e.g. Prochaska et al. 2005). However, to estimate the effect of galactic H\(_i\) on 21-cm fluctuation statistics during the reionization epoch, we must extrapolate to higher redshift. There are two competing factors. On the one hand, the collapsed fraction of mass rises as reionization progresses, which would imply a galactic H\(_i\) fraction that decreases towards high redshift. On the other hand, the fact that the H\(_i\) fraction is constant below \(z \sim 5\) suggests that the fraction of hydrogen within galaxies that is in H\(_i\) increases with redshift. In this paper, we conservatively assume that the fraction of gas within galaxies that is H\(_i\) increases at a rate that preserves the 2 per cent galactic H\(_i\) mass fraction (relative to the total hydrogen content of the Universe) into the reionization epoch.

This is obviously a fairly simplistic model. The actual physics of the H\(_i\) content in galaxies depends both on star formation and feedback processes within the galaxy, as well as on the intergalactic UV background. For instance, as the UV background falls towards high redshift, the H\(_i\) fraction within galaxies could increase, and perhaps conspires to cancel with the decreasing collapse fraction to maintain the observed roughly constant H\(_i\) fraction of \(\sim 2\) per cent, as seen from \(z \sim 1\) to \(z \sim 5\). Indeed, the fraction in protogalactic H\(_i\) may be even larger than the \(\sim 2\) per cent we assume in the pre-reionization epoch, particularly if there is a significant population of minihaloes\(^5\) with \(T_{\text{vir}} < 10^4\) K. Modelling this quantity is difficult and beyond the scope of this paper. For now, we note that our empirical extrapolation becomes increasingly uncertain at high redshift; it is probably reasonable in the redshift range \(z \sim 6\)–8, where some of the most interesting effects (such as the change of sign of the cross-correlation between galaxies and 21-cm emission) take place.

3 SEMINUMERICAL SIMULATIONS

In this paper, we investigate the statistics of 21-cm fluctuations including galactic H\(_i\) in a seminumerical model for the reionization of a three-dimensional volume of the IGM (Mesinger & Furlanetto 2007; Zahn et al. 2007; Geil & Wyithe 2008). Our seminumerical simulations are based on an analytic model for the reionization of the IGM, which we describe first.

3.1 Density-dependent analytic model of reionization

In regions of the IGM that are overdense, galaxies will be overabundant for two reasons: first because there is more material per unit volume to make galaxies, and second because small-scale fluctuations need to be of lower amplitude to form a galaxy when embedded in a larger-scale overdensity (the so-called galaxy bias; see Mo & White 1996). Regarding reionization of the IGM, the first effect will result in a larger density of ionizing sources. However, this larger density will be compensated by the increased density of gas to be ionized, which also increases the recombination rate. The process of reionization also contains several layers of feedback. Radiative feedback heats the IGM and results in the suppression of low-mass galaxy formation (Efstathiou 1992; Quinn, Katz & Efstathiou 1996; Thoul & Weinberg 1996; Dijkstra et al. 2004). Such feedback effects can potentially be more intense in overdense regions, leading to weaker galaxy formation bias than might be expected from simple linear bias models (Kramer, Haiman & Oh 2006). Probing the morphology of reionization could potentially lead to constraints on such feedback effects.

\(^1\) http://www.lofar.org/
\(^2\) http://www.haystack.mit.edu/ast/arrays/mwa/
\(^3\) http://astro.berkeley.edu/~dbacker/eor/
\(^4\) http://www.skatelescope.org/
\(^5\) Since these are photoevaporated as reionization progresses (Shapiro, Iliev & Raga 2004), they will reside primarily in neutral regions, and present an additional biased H\(_i\) contribution that is anticorrelated with galaxies but which we do not model here.
To compute the relation between the local overdensity and the brightness temperature of redshifted 21-cm emission, we use the model described in Wyithe & Loeb (2007). The evolution of the ionization fraction by mass \( Q_{\delta,R} \) of a particular region of IGM with scale \( R \) and overdensity \( \delta \) (at observed redshift \( z_{\text{obs}} \)) may be written as

\[
\frac{dQ_{\delta,R}}{dt} = \frac{N_{\text{ion}}}{0.76} \left[ Q_{\delta,R} \frac{dF_{\text{col}}(\delta, R, z, M_{\text{ion}})}{dt} + (1 - Q_{\delta,R}) \frac{dF_{\text{col}}(\delta, R, z, M_{\text{ion}})}{dt} \right] - \alpha_{b}C_{n}^{\text{HI}} \left( 1 + \frac{\sigma_{\text{R}}}{\sqrt{2} \left[ (\sigma_{\text{gal}})^{2} - (\sigma(R))^{2} \right]} \right) \left( 1 + z \right)^{3} Q_{\delta,R},
\]

where \( N_{\text{ion}} \) is the number of ionizing photons entering the IGM per baryon in galaxies, \( \alpha_{b} \) is the case-B recombination coefficient, \( C = 2 \) is the clumping factor (which we assume, for simplicity, to be constant) and \( D(z) \) is the growth factor between redshift \( z \) and the present time. The production rate of ionizing photons in neutral regions is assumed to be proportional to the collapsed mass fraction \( F_{\text{col}}(\delta, R, z, M_{\text{ion}}) \), where in neutral regions the minimum halo mass \( (M_{\text{min}}) \) is limited by the Jeans mass in an ionized IGM. We assume \( M_{\text{min}} \) to correspond to a virial temperature of 10⁵ K, representing the hydrogen cooling threshold, and \( M_{\text{ion}} \) to correspond to a virial temperature of 10⁴ K, representing the mass below which infall is suppressed from an ionized IGM (Dijkstra et al. 2004). In a region of comoving radius \( R \) and mean overdensity \( \delta(z) = \delta D(z)/D(z_{\text{obs}}) \) (specified at redshift \( z \) instead of the usual \( z = 0 \)), the relevant collapsed fraction is obtained from the extended Press–Schechter (Press & Schechter 1974) model (Bond et al. 1991) as

\[
F_{\text{col}}(\delta, R, z) = \text{erfc} \left( \frac{\delta - \delta(z)}{\sqrt{2 \left[ (\sigma_{\text{gal}})^{2} - (\sigma(R))^{2} \right]} \right),
\]

where \( \text{erfc}(x) \) is the complementary error function, \( \sigma^{2}(R) \) is the variance of the density field smoothed on a scale \( R \) and \( \sigma_{\text{gal}}^{2} \) is the variance of the density field smoothed on a scale \( R_{\text{gal}} \), corresponding to a mass scale of \( M_{\text{min}} \) or \( M_{\text{ion}} \) (both evaluated at redshift \( z \) rather than at \( z = 0 \)). In this expression, the critical linear overdensity for the collapse of a spherical top-hat density perturbation is \( \delta_{c} \approx 1.69 \).

The model assumes that on large (linear regime) scales most ionizing photons are absorbed locally, so that the ionization of a region is caused by nearby ionization sources. This assumption is certainly justified during the early stages of reionization, when the mean free path for ionizing photons is short. However, even later in the reionization process, the mean free path always remains smaller than the characteristic \( \text{H} \text{I} \) bubble size (it could be smaller if minihaloes or pockets of residual \( \text{H} \text{I} \) block ionizing photons between the sources and the edge of the \( \text{H} \text{I} \) region).

### 3.2 The ionization field

Our modelling follows the procedure outlined in Geil & Wyithe (2008), and we refer the reader to that paper for details of the model. The model employs a semi-analytic prescription for the reionization process, which is combined with a realization of the density field. We construct an ionization field based on a Gaussian random field for the overdensity of mass, combined with the value of the ionized fraction \( Q_{\delta,R} \) (equation 1) as a function of overdensity \( \delta \) and smoothing scale \( R \). We repeatedly filter the linear density field at logarithmic intervals on scales comparable to the box size down to the grid scale size. For all filter scales, the ionization state of each grid position is determined using \( Q_{\delta,R} \) and deemed to be fully ionized if \( Q_{\delta,R} \geq 1 \). All voxels within a sphere of radius \( R \) centred on these positions are flagged and assigned \( Q_{\delta,R} = 1 \), while the remaining non-ionized voxels are assigned an ionized fraction of \( Q_{\delta,R} = \min \), where \( \min \) corresponds to the smallest smoothing scale. A voxel forms part of an \( \text{H} \text{I} \) region if \( Q_{\delta,R} > 1 \) on any scale \( R \). In this paper, we present simulations corresponding to a linear density field of resolution 256, with a comoving side length of 512 Mpc. This procedure yields an ionization map \( Q_{\text{ion}}(x) \) as a function of position \( x \).

### 3.3 The galactic \( \text{H} \text{I} \) component

Having computed the ionization field, we then find the distribution of the galactic \( \text{H} \text{I} \) component. To model the cosmic density of collapsed \( \text{H} \text{I} \), we could assume that the star-forming galaxies responsible for reionization are the harbourers of galactic \( \text{H} \text{I} \). However, it is possible that the connection between galactic \( \text{H} \text{I} \) and star formation is not direct, either because there is \( \text{H} \text{I} \) remaining in older low-mass galaxies, or because the fraction of galactic gas that is \( \text{H} \text{I} \) is host mass dependent. As presented, our model is not able to address either of these issues. Therefore, to ascertain the possible range of influence that galactic \( \text{H} \text{I} \) might have on the 21-cm fluctuation statistics, we have assumed a characteristic mass \( M_{\text{col}} \) for the hosts of galactic \( \text{H} \text{I} \). Furthermore, rather than try to assign individual galaxies to the simulation we make the approximation that Poisson noise is negligible (as illustrated in Wyithe 2008) and assign a smooth \( \text{H} \text{I} \) density

\[
\rho_{\text{H}i}(x) = \rho_{\text{H}i,\text{col}}(1 + \rho_{\text{H}i}),
\]

where \( \rho_{\text{H}i,\text{col}} \) and \( \rho_{\text{H}i} \) are the mass-averaged densities of collapsed \( \text{H} \text{I} \) in galaxies and the total hydrogen density, respectively, and \( b(M_{\text{col}}, z) \) is the galaxy bias for a halo of mass \( M_{h} \) at redshift \( z \) (Sheth, Mo & Tormen 2001).

### 3.4 The 21-cm brightness temperature

Using the above model, we now compute the position-dependent brightness temperature of the simulation box, which becomes

\[
T_{\text{IGM}}(x) = 22 \text{ mK} \left( \frac{1 + z}{7.5} \right)^{1/2} \times \left[ (1 - Q_{\text{ion}})(1 + \delta) + Q_{\text{ion}}Q_{\text{H}i,\text{col}}(1 + b \delta) \right].
\]

This expression accounts for the effect of the neutral content of galaxies on the brightness temperature from ionized regions of the IGM. In neutral regions, the total \( \text{H} \text{I} \) content of the IGM is not affected by galaxy bias or the collapsed fraction.

Note that we only account for brightness temperature fluctuations due to variation in the density and ionization fraction of the IGM. We ignore variations in the spin temperature (which we assume to be always much greater than the CMB temperature) due to fluctuations in heating and radiative Lyα coupling; these are important primarily early in the reionization process, when galaxies are in any case rare.

Note also that our semianalytical model does not compute peculiar velocities, and so equation (4) does not include a peculiar velocity-induced enhancement of the brightness temperature in overdense regions (Barkana & Loeb 2005; Bharadwaj & Ali 2005). As in earlier sections, we consider a model in which the mean IGM is reionized at \( z = 6 \). We again assume that star formation proceeds.
in haloes above the hydrogen-cooling threshold in neutral regions of IGM. In ionized regions of the IGM, star formation is assumed to be suppressed by radiative feedback (see Section 3.1).

4 RESULTS

In this section, we present our results in four parts, beginning with redshift evolution of fluctuation statistics at a fixed angular scale, before discussing more subtle scale dependent effects in the later subsections. We illustrate the contribution of galactic H I to the 21-cm signal using the following example. We assume that the IGM was reionized at \( z = 6 \) (White et al. 2003; Fan et al. 2006; Gnedin & Fan 2006), and so first find the value of \( N_{\text{ion}} \) that yields overlap of ionized regions at the mean density IGM by that time. Using this constant value for \( N_{\text{ion}} \), we then integrate equation (1) as a function of \( \delta \) and \( R \). At a specified redshift, this yields the filling fraction of ionized regions within the IGM on various scales \( R \) as a function of overdensity for use in our seminumerical model.

4.1 The auto-correlation function of 21-cm intensity fluctuations

Since our seminumerical model computes the three-dimensional ionization structure of the IGM, including the effect of H II regions, we can use it to compute the evolution of variance in 21-cm emission among regions of fixed volume. After smoothing on a spatial scale corresponding to the angle \( \theta \), there is an observed probability distribution for brightness temperature \( T - \langle T \rangle \) (\( \theta \)). The second moment of this distribution corresponds to the auto-correlation function of brightness temperature smoothed on an angular scale \( \theta \):

\[
\xi \equiv \langle (T - \langle T \rangle)^2 \rangle,
\]

where the angular brackets denote spatial averages.

Examples of auto-correlation functions are shown in the left-hand panel of Fig. 1 as a function of redshift at \( \theta = 10 \) arcmin. Three lines are shown corresponding to values for \( M_{\text{gal}} \) of \( 10^9 \, M_\odot \), \( 10^{10} \, M_\odot \) and \( 10^{11} \, M_\odot \). The residuals are plotted above the main panel to show the magnitude of the error introduced when the galaxy contribution is ignored. Early in the reionization process, before the appearance of H II regions begins to dominate the fluctuation amplitude, the inclusion of a galactic H I fraction enhances the 21-cm fluctuations. However, in contrast to the mean signal (which is always larger by construction), the size of fluctuations is reduced by the presence of galaxies late in the reionization era. This reduction can be traced to the fact that galaxies are biased towards overdense regions, while neutral IGM is biased towards underdense regions which are reionized last. As a result, the inclusion of a galactic H I fraction reduces the intensity contrast between overdense and underdense regions. The size of the residuals shows that within this model, the 2 per cent galactic H I fraction reduces the fluctuation amplitude over a large fraction of the reionization epoch. At \( z \sim 7 \), it reduces the fluctuation amplitude by around 10 per cent (which makes sense, since galactic H I constitutes about 10 per cent of the total H I content of the universe at that point).

4.2 The cross-correlation between galaxies and 21-cm intensity fluctuations

The inclusion of galactic H I in the calculation of the 21-cm signal will also modify predictions for the cross-correlation of 21-cm emission with galaxies. The cross-correlation function of galaxy overdensity and brightness temperature smoothed on an angular scale \( \theta \) is

\[
\xi \equiv \langle (\tau - \langle \tau \rangle) \delta_g \rangle,
\]

where \( \delta_g = b_\tau \delta_g \), and \( b_\tau(M_g, z) \) is the galaxy bias for a halo of mass \( M_g \) at redshift \( z \). To calculate the cross-correlation function, we assume \( M_g = 10^{12} \, M_\odot \) for the host mass of observed galaxies throughout this paper. This host mass yields a density of galaxies that is comparable to the density observed in the Subaru Deep Fields (Kashikawa et al. 2006) at \( z \sim 6.6 \) (Furlanetto & Lidz 2007).

Examples of the cross-correlation functions are shown in the right-hand panel of Fig. 1 as a function of redshift at fixed angle (\( \theta = 10 \) arcmin). The inclusion of galactic H I reduces the amplitude of the cross-correlation function by about 10 per cent (relative to the case where galactic H I is ignored) late in the reionization era for the reasons discussed in Section 4.2. In addition, the cross-correlation between observed galaxies and fluctuations in 21-cm emission changes sign at overlap because the H I content of the Universe shifts from being dominated by the underdense regions of IGM to H I in galaxies (which reside in overdense regions). This sign change will provide an unambiguous pointer to the redshift at which reionization ends. Moreover, because the sign change will occur over a narrow frequency interval, it should provide an important

![Figure 1](https://example.com/image1.png)

**Figure 1.** Seminumerical model with fixed characteristic host mass for galactic H I. Left: the evolution of the auto-correlation function of brightness temperature with redshift (computed within regions of size 10 arcmin). Right: the evolution of the cross-correlation function with redshift (computed within regions of size 10 arcmin). In each case, the grey and dark lines correspond to models which exclude and include galactic H I, respectively. The small upper section of each panel shows the difference between the models including and without galactic H I.
check on possible sources of systematic error that could be present in measurements of the PS of intensity fluctuations which is always positive by construction.

### 4.3 21-cm power spectrum

Fig. 2 shows 21-cm PS computed from the seminumerical simulations at redshift intervals of Δz = 0.5 between redshifts z = 10 and z = 6. In each case, we plot the dimensionless PS Δ^2_21(k) = k^3/(2π^2) P_21(k), where P_21 is the PS of 21-cm fluctuations. Both the case of the IGM alone (Δ^2_IGM), and the case assuming a host mass of M_{col} = 10^{10} M_☉ for the galactic H I (Δ^2_{21, col}) are shown (lower panels). We also show the relative fluctuation δ_{21, col} = (Δ^2_21 - Δ^2_{21, col})/Δ^2_21 of the 21-cm PS owing to galactic H I (upper panels).

These figures illustrate several features of the 21-cm PS that have been previously discussed in the literature. First, at the highest redshifts considered, and before the IGM is significantly ionized in this model, the PS mimics the mass PS. Once the IGM is partially reionized following the appearance of the first galaxies, a shoulder appears in the PS that corresponds to the typical bubble scale, and which is due to the movement of power from small to large scales that accompanies the formation of H II regions. Within the band of wavenumbers where 21-cm observatories will be most sensitive (at around k ~ 0.1 Mpc⁻¹), the appearance of this shoulder leads to a rapid rise in the amplitude of the PS, followed by a decrease in power when most of the IGM has been ionized near the end of reionization. Since the amplitude of the 21-cm PS on large scales is sensitive to the size and bias of bubbles as well as to their number, the logarithmic gradient will provide a powerful model discriminant (Lidz et al. 2009), in addition to the amplitude.

The inclusion of galactic H I in these models affects both the amplitude and slope of the 21-cm PS in a qualitative way. First, the extra H I increases the amplitude of the 21-cm PS on large scales early in reionization, because both the neutral IGM and galactic H I are correlated with the density field in the same way. However, as reionization proceeds, the bubble formation is preferentially around overdense regions of the IGM. As a result, galaxy bias will ensure that the galactic H I is located preferentially inside the newly formed H II regions. The galactic H I will therefore be anticorrelated with the neutral IGM outside the H II regions, which, on scales larger than the H II region, leads to a relative decrease in the PS amplitude. Thus, the appearance of the first H II regions will coincide with a decrease in the PS amplitude prior to the aforementioned rise.

Furthermore, because the galactic H I is biased towards H II regions, the movement of power from small to large scales that produces the shoulder in the 21-cm PS is lessened when the contribution...
of galactic $\text{H}\text{i}$ is considered. As a result, the 21-cm PS at large scales evaluated from simulations, which include $\text{H}\text{i}$ in galaxies, is lower than the PS computed using the IGM alone. Observationally, this will impact on the slope of the measured 21-cm PS, which will be flatter than expected early in reionization and steeper once bubbles have formed relative to a model that accounts only for the IGM.

In summary, the effect of galactic $\text{H}\text{i}$ on the 21-cm PS is to change both the shape of the 21-cm PS as well as its amplitude. In Section 5, we demonstrate that the deviations between models that do and do not include galactic $\text{H}\text{i}$ will be detectable by future low-frequency telescopes, and that as a result, detailed analyses of the astrophysics of reionization using the 21-cm PS will need to account for the effect of galactic $\text{H}\text{i}$.

4.4 21-cm–galaxy cross power spectrum

The central and upper panels of Fig. 3 show the modulus of the dimensionless 21-cm–galaxy cross PS with $(\Delta_{21}^{\text{g},\text{col}})$ and without $(\Delta_{21}^{\text{g}})$ galactic $\text{H}\text{i}$ as well as the galactic $\text{H}\text{i}$ induced fluctuation $[\delta_{21}^{\text{g},\text{col}} = (\Delta_{21}^{\text{g},\text{col}} - \Delta_{21}^{\text{g}})/\Delta_{21}^{\text{g}}]$, computed from the seminumerical simulations at $z = 7$ (left) and $z = 9$ (right). A host mass of $M_{\text{col}} = 10^{10}$ $\text{M}_\odot$ is considered for the galactic $\text{H}\text{i}$. An observed galaxy mass of $M_g = 10^{11}$ $\text{M}_\odot$ is assumed. In the lower panels of Fig. 3, we show the corresponding coefficient of the 21-cm–galaxy cross PS.

Since overdense regions, where galaxies are concentrated, are reionized first these figures show an anticorrelation on large scales, which drops in strength to zero on small scales after the formation of $\text{H}\text{II}$ regions. We find that the inclusion of galactic $\text{H}\text{i}$ lessens the amplitude of the anticorrelation, since a fraction of $\text{H}\text{i}$ is now colocated with the galaxies inside $\text{H}\text{II}$ regions. In addition, the cross PS changes sign on small scales which reflects the correlation of galaxies with the galactic $\text{H}\text{i}$ inside the $\text{H}\text{II}$ regions, where no power is contributed in 21-cm fluctuations of the IGM. Thus, with the caveat that galaxies can be selected without bias from IGM absorption (which may not be true if, for instance, the galaxies are selected in Ly$\alpha$ emission; see Lidz et al. 2009 for discussion of the latter case), the scale at which the 21-cm–galaxy cross PS changes sign could be used to probe the scale of $\text{H}\text{II}$ regions late in the reionization era.

5 SENSITIVITY TO THE EFFECT OF GALACTIC $\text{H}\text{i}$ ON 21-CM FLUCTUATIONS

Before concluding, we compute the sensitivity with which the effect of galactic $\text{H}\text{i}$ could be detected using forthcoming low-frequency arrays.

5.1 Sensitivity to the 21-cm PS

To compute the sensitivity $\Delta P_{21}(k)$ of a radio interferometer to the 21-cm PS, we follow the procedure outlined by McQuinn et al. (2006) and Bowman et al. (2007) (see also Wyithe, Loeb & Geil 2008). The important issues are discussed below, but the reader is referred to these papers for further details. The sensitivity to the PS comprises components due to the thermal noise, and due to sample
variance within the finite volume of observations. We consider observational parameters corresponding to the design specifications of the MWA, and of a hypothetical follow-up to the MWA (termed the MWA5000). In particular, the MWA is assumed to comprise a phased array of 500 tiles. Each tile contains 16 cross-dipoles to yield an effective collecting area of $A_t = 16(\lambda^2/4\pi)$ (the area is capped for $\lambda > 2.1$ m). The physical area of a tile is $A_{\text{tile}} = 16$ m$^2$. The tiles are distributed according to a radial antenna density of $\rho(r) \propto r^{-2}$, within a diameter of 1.5 km and outside of a flat density core of radius 18 m. The MWA5000 is assumed to follow the basic design of the MWA. The quantitative differences are that the telescope is assumed to have 5000 tiles within a diameter of 2 km, with a flat density core of 80 m. In each case, we assume one field is observed for 1000 h. Following the work of McQuinn et al. (2006), we assume that foregrounds can be removed over 8 MHz bins, within a bandpass of 32 MHz [foreground removal therefore imposes a minimum on the wavenumber accessible of $k_{\min} \sim 0.04([1+z]/7.5)^{-1}$ Mpc$^{-1}$).

The sensitivity to the 21-cm PS per mode may be written

$$\delta P_{21}(k, \theta) = \frac{T_{\text{sky}}^2 \Delta D}{\Delta V_{\text{int}} n(k, \zeta)} \left( \frac{\lambda^2}{A_e} \right)^2 + P_{21}(k, \theta),$$

where $D$ is the comoving distance to the centre of the survey volume which has a comoving depth $\Delta D$. Here, $n(k, \zeta)$ is the density of baselines which observe a wavevector with transverse component $k_\perp$, and $\theta$ is the angle between the mode $k$ and the line of sight. The thermal noise component (first term) is proportional to the sky temperature, where $T_{\text{sky}}^2 \sim 250(\pi k T)^{-6}$ K at the frequencies of interest. The second term corresponds to sample variance. The overall sensitivity is

$$\Delta P_{21}(k, \theta) = \delta P_{21}(k, \theta)/\sqrt{N_s(k, \theta)},$$

where $N_s(k, \theta)$ denotes the number of modes observed in a k-space volume $d^3k$ (only modes whose line-of-sight components fit within the observed bandpass are included). In terms of the k-vector components $k$ and $\theta$, $N_s = 2\pi k^2 \sin \theta \, d\theta \, dk \, d\psi / (2\pi^2)$ where $V = D^2 \Delta D (\lambda^2/A_e)$ is the observed volume. Taking the spherical average over bins of $\theta$, the sensitivity to the 21-cm PS is

$$\frac{1}{[\Delta P_{21}(k)]^2} = \sum_{\theta} \frac{1}{[\Delta P_{21}(k, \theta)]^2}.$$  

The spherically averaged sensitivity curves for the MWA (within bins of $\Delta k = k/10$) are plotted as the dotted lines in the lower panels of Fig. 2. The sensitivity as a ratio of the PS computed without a galactic H I contribution ($\Delta P_{21}/P_{21}$) is plotted in the upper panels of Fig. 2 (again as dotted lines). These estimates illustrate that late in reionization, the effect of the galactic H I will be at a level above the sensitivity of the first generation low-frequency arrays. However, the low resolution of the MWA would mean that the shape-change of the PS owing to the galactic H I would not be detected until very close to overlap. The corresponding sensitivity curves for the MWA5000 are plotted as the thin grey lines in Fig. 2. The larger collecting area of the MWA5000 would allow the effect of galactic H I to be detected out to higher redshifts and at smaller scales.

5.2 Sensitivity to the 21-cm–galaxy cross PS

To compute the sensitivity of the MWA to the 21-cm–galaxy cross PS ($P_{21g}$), we follow the discussion of Furlanetto & Lidz (2007). The sensitivity to a particular mode is

$$2[\delta P_{21g}(k, \theta)]^2 = [P_{21g}(k, \theta)]^2 + \delta P_{21g}(k, \theta) \delta P_{g}(k, \theta),$$

where $\delta P_{21g}(k, \theta) = b^2 P_{21}(k, \theta) + n_{g}^{-1}$ is the uncertainty in the galaxy PS and $P_{g}$ is the underlying mass PS at redshift $z$. In the second term, $n_{g}$ is the density of galaxies, which we approximate as $n_{g} = M_g \delta n/dM_g$, where $\delta n/dM$ is the Press–Schechter (1974) mass function and $M_g$ is the halo mass of galaxies in the survey. After calculation of the total sensitivity

$$\Delta P_{21g}(k, \theta) = \delta P_{21g}(k, \theta)/\sqrt{N_s(k, \theta)},$$

and taking the spherical average over bins of $\theta$ as before, the sensitivity to the 21-cm–galaxy cross PS is

$$\frac{1}{[\Delta P_{21g}(k)]^2} = \sum_{\theta} \frac{1}{[\Delta P_{21g}(k, \theta)]^2}.$$  

The spherically averaged sensitivity curves for the MWA (within bins of $\Delta k = k/10$) are plotted as the dotted lines in the central panels of Fig. 3. The sensitivity as a ratio of the fiducial IGM-only PS ($\Delta P_{21g}/P_{21g}$) is also plotted in the upper panels of Fig. 3. Here, we have made the very optimistic assumption that galaxies have been detected down to a resolution limit corresponding to a host mass of $M_g = 10^{11} M_\odot$ over the full MWA field ($\sim 900$ square degrees). These sensitivity estimates illustrate that the effect of the galactic H I on the cross-correlation between galaxies and 21-cm emission could be detected with the first generation low-frequency arrays. Moreover, the resolution of the MWA would be sufficient to detect the sign change of the 21-cm–galaxy cross PS at the scale of the H II regions late in reionization. The limitation on measurement of the 21-cm–galaxy cross-correlation may therefore lie with the feasibility of obtaining a deep spectroscopic survey over an area that is hundreds of times larger than the current state of the art. The corresponding sensitivity curves for the MWA5000 are also plotted as the thin grey lines in Fig. 3. The larger collecting area of the MWA5000 would greatly increase the significance with which the effect of galactic H I could be measured.

6 CONCLUSION

In this paper, we have investigated the impact of H I in galaxies on the statistics of 21-cm fluctuations using seminumerical models. Our models are unable to self-consistently compute the galactic H I content of galaxies prior to the end of reionization. As an input to our model, we have therefore assumed that during the reionization era 2 per cent of hydrogen is in the form of H I and located within galaxies. This number is motivated by observations of the mass-weighted fraction of cosmic hydrogen in H I after the end of reionization, which is dominated by damped absorption systems and which has a constant value of $\sim 2$ per cent between $z \sim 1$ and $z \sim 5$.

Our modelling shows that this assumption results in a reduction of 10–20 per cent in the amplitude of 21-cm fluctuations over a range of spatial scales, and over a large fraction of the reionization era. However, importantly, the effect of galactic H I is also to change the shape of the 21-cm PS rather than just the amplitude. In particular, we find that because the galactic H I is biased towards H II regions, the H II region induced shoulder in the PS is less prominent when the contribution of galactic H I is considered. The amplitude of the 21-cm PS is modified in a scale-dependent way by up to 20 per cent when a 2 per cent galactic H I fraction is included. Of
course, the galactic H\textsc{i} fraction is very uncertain at high redshift. However, we find that the fractional modification of the 21-cm fluctuation statistics is approximately proportional to the density of galactic H\textsc{i}. Therefore, if we assume a value lower (higher) than the 2 per cent observed at $z < 5$, then our results for the error introduced through neglect of galactic H\textsc{i} will be over(under)estimated. On the other hand, the change of sign in the cross-correlation between galaxies and the 21-cm signal is robust to our assumptions.

We have also modelled the cross-correlation between galaxies and 21-cm emission. We find that the inclusion of galactic H\textsc{i} lessens the amplitude of the anticorrelation between galaxies and 21-cm emission since a fraction of H\textsc{i} is now collocated with the galaxies inside the H\textsc{ii} regions. In addition, the cross PS changes sign on small scales, which reflects the correlation of galaxies with the galactic H\textsc{i} inside the H\textsc{ii} regions, where no power is contributed in 21-cm fluctuations of the IGM. Thus, the scale at which the 21-cm–galaxy cross PS changes sign could be used to probe the scale of H\textsc{ii} regions late in the reionization era. Finally, we note that the cross-correlation between galaxies and 21-cm emission will change sign at the end of the reionization era, providing an alternative avenue to pinpoint the end of reionization.

We have estimated the sensitivity of the MWA to the spherically averaged 21-cm PS and 21-cm–galaxy cross PS. Our calculations illustrate that the effect of the galactic H\textsc{i} on 21-cm fluctuations is at a level that would be significant with respect to the sensitivity of the MWA late in reionization. However, the low resolution of the MWA would mean that the shape change of the PS owing to the galactic H\textsc{i} could not be detected until very close to overlap. On the other hand, when combined with a suitable galaxy redshift survey, the resolution of the MWA would be sufficient to detect the sign change of the 21-cm–galaxy cross PS at the scale of the H\textsc{ii} regions late in reionization. A follow-up telescope comprising 10 times the collecting area of the MWA would measure the effects of galactic H\textsc{i} with high significance.

In summary, our modelling shows that the H\textsc{i} content of the galaxies that reionize the universe provides a significant contribution to the statistics of 21-cm fluctuations. The galactic H\textsc{i} contribution to the 21-cm intensity will therefore need to be considered in detailed modelling of the 21-cm intensity PS in order to correctly interpret measurements from the next generation of low-frequency arrays.

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