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The correlation between star formation and 21-cm emission during the reionization epoch

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ABSTRACT
Reionization is thought to be dominated by low-mass galaxies, while direct observations of resolved galaxies probe only the most massive, rarest objects. The cross-correlation between fluctuations in the surface brightness of the cumulative Lyα emission (which serves as a proxy for the star formation rate) and the redshifted 21-cm signal from neutral hydrogen in the intergalactic medium (IGM) will directly probe the causal link between the production of ionizing photons in galaxies and the reionization of the IGM. We discuss the prospects for detecting this cross-correlation for unresolved galaxies. We find that on angular scales ≲10 arcmin detection will be practical using wide-field near-infrared (near-IR) imaging from space in combination with the forthcoming Mileura Wide-field Array – Low Frequency Demonstrator. When redshifted 21-cm observations of the neutral IGM are combined with space-based near-IR imaging of Lyα emission, the detection on angular scales ≲3 arcmin will be limited by the sensitivity of the 21-cm signal, even when a small-aperture optical telescope (∼2 m) and a moderate field of view (∼10 deg²) are used. On scales ≳3 arcmin, the measurement of cross-correlation will be limited by the accuracy of the foreground sky subtraction.

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

1 INTRODUCTION
The primary goals for studies of the reionization epoch are to determine the nature of the first generation of galaxies, and to observe the causal link between these galaxies and the ionization state of the intergalactic medium (IGM). At the current time, direct observations of resolved galaxies probe only the most massive, rarest objects (Stark, Loeb & Ellis 2007, and references therein). It has been shown that these massive galaxies should correlate with the redshifted 21-cm signal from diffuse neutral hydrogen in the IGM prior to the completion of reionization owing to the biased galaxy formation in overdense regions (Furlanetto & Lidz 2007; Wyithe & Loeb 2007). However, these massive galaxies are not responsible for the bulk of the ionizing photons that reionized the IGM. Rather, reionization was dominated by low-mass galaxies, with luminosities below current detection thresholds (Ellis 2007, and references therein). The emission of these unresolved galaxies should therefore also be correlated with the ionization of the IGM, and by extension, with the redshifted 21-cm signal. In this paper we suggest that the cross-correlation between the luminosity density of unresolved Lyα emission and the redshifted 21-cm intensity will directly probe the connection between the reionization of the IGM and the star formation rate (and hence the production of ionizing photons). We compute the expected amplitude of this cross-correlation, and discuss the prospects for its detection.

Star formation at high redshift has been studied using fluctuations in unresolved near-infrared (near-IR) broad-band emission (e.g. Kashlinsky et al. 2005). Since the fluctuations from star formation at high redshift are superimposed on fluctuations from foreground galaxies at low redshift, these measurements have required subtraction of a model for the fluctuating foreground component. In this paper we discuss removal of the foreground fluctuations statistically using the fact that these are uncorrelated with the redshifted 21-cm emission. The measurement of 21-cm emission is also subject to a fluctuating foreground, which will be correlated with the foreground in the Lyα observations. However, it is proposed as part of upcoming 21-cm experiments, that the redshifted 21-cm foreground be removed using the smoothness of the spectrum of foreground sources, which will be compared with the rapid frequency fluctuations of the 21-cm signal (Morales, Bowman &
This subtraction method will reveal the narrow-band 21-cm fluctuations, but will not allow detection of broad-band 21-cm fluctuations. Therefore, rather than considering fluctuations in broad-band flux from high-reddish star formation, in this paper we instead discuss narrow-band near-IR observations. The fluctuations in flux within narrow-band observations would be dominated by the Lyα line of galaxies in a narrow redshift interval, and would therefore be the appropriate choice for detecting the cross-correlation between the signals.

Any model for the reionization of the IGM must describe the relation between the emission of ionizing photons by stars in galaxies and the ionization state of the intergalactic gas. This relation is non-trivial as it depends on various internal parameters (which may vary with galaxy mass), such as the fraction of the gas within galaxies that is converted into stars and accreting black holes, the spectrum of the ionizing radiation, and the escape fraction of ionizing photons from the surrounding interstellar medium (ISM) as well as the galactic halo and its immediate infalling region (see Loeb 2006, for a review). The relation also depends on intergalactic physics. In regions of the IGM that are overdense, galaxies will be overabundant because small-scale fluctuations need to be of lower density (Mo & White 1996). On the other hand, the increase in overdensity and the brightness temperature of redshifted 21-cm emission of low-mass galaxy formation (Efstathiou 1992; Quinn, Katz & Efstathiou 1996; Tully & Weinberg 1996; Dijkstra et al. 2004). This delays the completion of reionization by lowering the local star formation rate, but the effect is counteracted in overdense regions by the biased formation of massive galaxies. Most models predict that the sum of these effects is dominated by galaxy bias, and that as a result overdense regions are reionized first. It follows that the cross-correlation between the star formation rate density and redshifted 21-cm emission should be negative, as has been suggested for the cross-correlation between massive galaxies and redshifted 21-cm emission (Furlanetto & Lidz 2007; Wyithe & Loeb 2007).

A measurement of the expected anticorrelation between the local star formation rate and the ionization state of the IGM, would provide crucial evidence in favour of the stellar ultraviolet (UV) reionization model over alternative models in which reionization resulted from decaying particles (Hansen & Haiman 2004; Biermann & Kusenko 2006; Kasuya & Kawasaki 2007; Ripamonti, Mapelli & Ferrara 2007) or from a more diffuse X-ray background (Madau et al. 2004; Ricotti, Ostriker & Gnedin 2005). In this paper we examine the feasibility of making this important measurement based on a simple illustrative model for stellar reionization, described in Section 2. We then derive the cross-correlation between the star formation rate and 21-cm emission in Section 3, before discussing the prospects for its detection in Section 4. Throughout the paper we adopt the set of cosmological parameters determined by Wilkinson Microwave Anisotropy Probe (Spergel et al. 2007) for a flat $\Lambda$CDM universe.

2 DENSITY-DEPENDENT MODEL OF REIONIZATION

In this paper we compute the relation between the local dark matter overdensity and the brightness temperature of redshifted 21-cm emission based on the model described in Wyithe & Loeb (2007). Here we summarize the main features of the model and refer the reader to that paper for more details.

The evolution of the ionization fraction by mass $Q_{\delta R}$ of a particular region of scale $R$ with overdensity $\delta$ (at observed redshift $z_{\text{obs}}$) may be written as

$$
\frac{dQ_{\delta R}}{dr} = \frac{N_{\text{ion}}}{0.76} \left[ Q_{\delta R} \frac{dT_{\text{coll}}}{d\delta R, z, M_{\text{ion}}} \right] + \left( 1 - Q_{\delta R} \right) \frac{dT_{\text{coll}}}{d\delta R, z, M_{\text{min}}} - \alpha_{\text{B}} C_{N, \text{gal}} \left[ 1 + \delta \frac{D(z)}{D(z_{\text{obs}})} \right] (1 + z)^3 Q_{\delta R},
$$

where $N_{\text{ion}}$ is the number of photons entering the IGM per baryon in galaxies, $\alpha_B$ is the case-B recombination coefficient, $C$ 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 fraction $F_{\text{coll}}$ of mass in haloes above the minimum threshold mass for star formation ($M_{\text{min}}$), while in ionized regions the minimum halo mass is limited by the Jeans mass in an ionized IGM ($M_{\text{ion}}$). We assume $M_{\text{min}}$ to correspond to a virial temperature of $10^4$ K, representing the hydrogen cooling threshold, and $M_{\text{ion}}$ to correspond to a virial temperature of $10^5$ K, representing the mass below which infall is suppressed from an ionized IGM (Dijkstra et al. 2004). In a region of comoving radius $R_{\delta R}$ 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 (1974) model (Bond et al. 1991) as

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

where $\text{erfc}(x)$ is the error function, $\sigma(R)$ is the variance of the density field smeared on a scale $R$, and $\sigma_{\text{gal}}$ is the variance of the density field smeared on a scale $R_{\delta R}$, 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 $\delta_{\text{c}} \approx 1.69$.

Equation (1) may be integrated as a function of $\delta$. At a specified redshift, this yields the filling fraction of ionized regions within the IGM on various scales $R$ as a function of overdensity. We may then also calculate the corresponding 21-cm brightness temperature contrast

$$
T(\delta, R) = 22 \text{mK} (1 - Q_{\delta R}) \left( \frac{1 + z}{7.5} \right)^{0.5} \left( 1 + 4 \frac{\delta}{3} \right),
$$

where the pre-factor of $4/3$ on the overdensity refers to the spherically averaged enhancement of the brightness temperature due to peculiar velocities in overdense regions (Barkana & Loeb 2005; Bharadwaj & Ali 2005).

Before proceeding we briefly comment on the range of applicability of the model [see Wyithe & Morales (2007) for a more detailed discussion]. The model assumes that on large (linear-scale) 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 H II bubble size (it could be smaller if minihaloes or pockets of residual H I block ionizing photons between the sources and the edge of the H II region). Our local ionization assumption is therefore valid as long as the characteristic bubble
size is smaller than the spatial scale of the correlations we consider. This requirement is met in regimes where the fraction of regions at a particular scale that are fully ionized is very low. In this paper we compute fluctuation statistics at \( z = 7 \) for scales as small as 0.6 arcmin. However, our model begins to break down on scales below \( \sim 1 \) arcmin, where at \( z = 7 \), 10 per cent of regions have already been reionized on this scale (Wyithe & Morales 2007).

3 THE \( \text{Ly}^\alpha \) LUMINOSITY DENSITY

The density-dependent model described in the previous section may be used to estimate the cross-correlation between star formation rate and the ionization state of the IGM. In this section, we begin by computing the star formation rate. Then, in subsequent sections we estimate the autocorrelation functions (i.e. the correlation functions at zero lag) for both star formation rate and 21-cm brightness temperature, as well as the cross-correlation between star formation rate and 21-cm brightness temperature.

The UV luminosity of galaxies is largest during periods of active star formation. In the dense environments within the high-redshift ISM the density of neutral hydrogen can be substantial, resulting in absorption of the majority of the UV photons produced. Recombinations in the ionized hydrogen then in turn produce \( \text{Ly}^\alpha \) photons. The \( \text{Ly}^\alpha \) emission from high-redshift galaxies is therefore powered by concurrent star formation. In this paper we assume \( \text{Ly}^\alpha \) emissivity to be a proxy for the star formation rate, and so begin by computing the luminosity density of \( \text{Ly}^\alpha \) photons. Given an ionizing photon production rate

\[
\log_{10} \left( \frac{J}{s^{-1}} \right) = 53.8 + \log_{10} \left( \frac{\dot{M}}{\dot{M}_{\odot} \text{yr}^{-1}} \right) - 0.0029 \left[ 9 + \log_{10}(Z) \right]^{2.5},
\]

(4)

where \( \dot{M} \) is the star formation rate per comoving \( \text{Mpc}^3 \), and \( Z \) the metallicity of a stellar population with a Salpeter initial mass function, the luminosity of \( \text{Ly}^\alpha \) entering the IGM is

\[
\Gamma = 2h_{\nu} \frac{v_{\nu}}{3} (1 - f_{\text{esc}}) / T I,
\]

(5)

where \( f_{\text{esc}} \) is the escape fraction of ionizing photons, \( h_{\nu} \) is Planck’s constant and \( v_{\nu} \) is the frequency of the \( \text{Ly}^\alpha \) transition. The transmission of \( \text{Ly}^\alpha \) photons through the IGM (\( T \)) is less than unity and is discussed below. In the above expressions we evaluate the star formation rate within a region of comoving radius \( R \) as

\[
\dot{M} = f_{\text{star}} \frac{\Omega_b}{\Omega_m} \rho_m (1 + \delta) \left[ (1 - Q_{\text{esc}}) \frac{dF_{\text{coll}}(\delta, R, M_{\text{min}})}{dt} \right] + Q_{\text{esc}} \frac{dF_{\text{coll}}(\delta, R, M_{\text{esc}})}{dt}.
\]

(6)

Here \( f_{\text{star}} \) is the star formation efficiency, \( \Omega_b \) and \( \Omega_m \) are the density parameters in matter and baryons, and \( \rho_m \) is the average comoving mass density in the Universe.

It is possible that the mass function of stars in \( \text{Ly}^\alpha \) emitting galaxies is top-heavy, in which case the \( \text{Ly}^\alpha \) luminosity could be an order of magnitude greater than suggested by equations (4) and (5). Indeed Dijkstra & Wyithe (2007) have noted that this must be the case due to the large observed equivalent widths in known Ly\( \alpha \) emitters, and the small value of \( \text{Ly}^\alpha \) transmission through the IGM (Dijkstra, Lidz & Wyithe 2007b). However, Dijkstra & Wyithe (2007) also argue that while top-heavy star formation must be present in many high-redshift \( \text{Ly}^\alpha \) emitters, in order to be consistent with additional observations the top-heavy formation phase must last for less than 10 per cent of the star formation time-scale in individual galaxies. As a result, Dijkstra & Wyithe (2007) find that the total \( \text{Ly}^\alpha \) emission is dominated by a normal stellar population when averaged over the full star formation history of galaxies at \( z \sim 6 \).

3.1 The transmission of \( \text{Ly}^\alpha \) photons through the IGM

Due to the strength of the \( \text{Ly}^\alpha \) resonance, a significant fraction of \( \text{Ly}^\alpha \) flux is absorbed in the infalling IGM surrounding a galaxy (Dijkstra et al. 2007b). The quantity \( T \) in equation (5) is the transmission of \( \text{Ly}^\alpha \) photons through the IGM, and corresponds to the fraction of \( \text{Ly}^\alpha \) photons leaving the galaxy that propagate to an observer. We assume the absorption of \( \text{Ly}^\alpha \) photons in the IGM to be dominated by neutral hydrogen, with a negligible contribution from dust (due to the low metallicity of the high-redshift IGM). We also ignore absorption of \( \text{Ly}^\alpha \) photons by dust within the galaxy due to the low metallicity of high-redshift stellar populations. In biased models of reionization, overdense regions are reionized first due to their being regions of greater than average star formation. Thus overdense regions produce positive fluctuations in the luminosity density of galactic \( \text{Ly}^\alpha \) emission. Conversely, neutral hydrogen is located preferentially in under dense regions, which will therefore be sites of lower \( \text{Ly}^\alpha \) transmission. As a result, the variable transmission of \( \text{Ly}^\alpha \) photons could serve to increase the clustering of \( \text{Ly}^\alpha \) galaxies. McQuinn et al. (2007), and hence to also increase the amplitude of fluctuations in the density of \( \text{Ly}^\alpha \) emission. Recently, Dijkstra et al. (2007b) have conducted a detailed investigation of the \( \text{Ly}^\alpha \) absorption properties of the IGM surrounding an \( \text{Ly}^\alpha \) emitting galaxy. This work concluded that the ionized IGM introduces significant absorption, and that as a result the \( \text{Ly}^\alpha \) transmission is only weakly dependent on the ionization state of the IGM. In particular, \( \text{Ly}^\alpha \) flux from a galaxy embedded in an H\text{II} region rather than in a reionized IGM will be subject to only a small amount of additional absorption due to the damping wing of the \( \text{Ly}^\alpha \) resonance. Rather than introduce a complex model for transmission, in this paper we instead assume the transmission to have the same value for all galaxies, and to be independent of overdensity. As a result we may underestimate the amplitude of \( \text{Ly}^\alpha \) fluctuations. The increased fluctuations introduced by variable transmission would increase the amplitude of the cross-correlation signal between \( \text{Ly}^\alpha \) and redshifted 21-cm emission. By assuming constant transmission we therefore arrive at conservative estimates for the detectability of the cross-correlation signal.

3.2 Diffuse \( \text{Ly}^\alpha \) emission from the IGM

In calculating the \( \text{Ly}^\alpha \) luminosity density we have neglected the potential contribution from a recombining IGM. We now show that this process provides a negligible contribution. To see this we note that at \( z = 7 \), around 10 per cent of baryons are collapsing inside galaxies per Hubble time, and that some fraction of these form stars (\( \sim 30 \) per cent). For every baryon taking part in star formation, around 4000 ionizing photons are produced (e.g. Barkana & Loeb 2001). Most ionizing photons do not escape the galaxy, and each of these produces 2/3 of an \( \text{Ly}^\alpha \) photon. Of the \( \text{Ly}^\alpha \) photons produced, some (\( \sim 70 \) per cent) will be absorbed in the IGM surrounding the galaxy. Hence we find \( \sim 4000 \times 0.1 \times 0.3 \times (2/3) \times (1 - 0.7) \), or around 25 photons per baryon are produced by galaxies during 1 Hubble time. On the other hand, at the redshift of interest, the recombination rate per baryon is around once per Hubble time, yielding the order of 2/3 \( \text{Ly}^\alpha \) photons per baryon per Hubble time from
the diffuse IGM. This number is 1.5 orders of magnitude smaller than the galactic Lyα emission. A more quantitative estimate of this ratio \( R_{Ly} \) is

\[
R_{Ly} \sim 50 \left[ \frac{\dot{f}_\gamma}{d\Phi_{col}/dt} \right] \left[ \frac{(f_{nat}T)N_f}{400} \right] \left( \frac{1+z}{10} \right)^{-3/2} \left( \frac{\bar{Q}}{0.5} \right)^{-1},
\]

(7)

where \( \bar{Q} \) and \( F_{col} \) are the average ionized fraction and collapsed fraction in the IGM, respectively, and \( N_f \) is the number of ionizing photons produced per baryon incorporated into stars.

### 4 FIDUCIAL MODEL FOR REIONIZATION

In this paper we show results for the cross-correlation between Lyα and 21-cm emission for a model that reionizes the mean IGM at \( z = 6 \) (White et al. 2003). In this model we 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 2). In what follows we present estimates of fluctuations in flux due to sources at \( z = 7 \), at which time the IGM is around 70 per cent ionized in this model.

### 5 VARIATION OF Lyα EMISSION WITH OVERDENSITY

The top left-hand panel of Fig. 1 shows the luminosity density [erg s\(^{-1}\) (comoving Mpc\(^{-1}\)] in the Lyα line as a function of the large-scale overdensity (\( \delta \)). To calculate the level of observed Lyα emission, we require an estimate of the product \( f_{nat}T \) (only the product of these parameters enters the observed luminosity). In a recent analysis Dijkstra, Wyithe & Haiman (2007a) have used semi-analytic models to constrain this parameter using the observed luminosity function of Lyα emitting galaxies at \( z = 5.7 \) and 6.5. The constraint is sensitive to the lifetime of the Lyα emission, but is expected to fall in the range \( 0.03 \lesssim f_{nat}T \lesssim 0.1 \). Here, and in the remainder of this paper we assume the product \( T f_{nat} = 0.1 \) when considering the properties of high-redshift Lyα emitters.

### 6 AUTOCORRELATION FUNCTIONS FOR STAR FORMATION AND 21-cm EMISSION

Before discussing the cross-correlation of star formation rate (Lyα emission) with 21-cm emission, we first compute each of the autocorrelation functions (i.e. the correlation functions at zero lag) individually. On comoving scales \( R \) larger than the characteristic bubble size (\( \gtrsim 1 \) arcmin at \( z = 7 \) in our model), we are able to compute the autocorrelation function \( \langle \xi_f^2(\theta) \rangle \) of fluctuations in brightness temperature \( T \) smoothed with top-hat windows of angular radius \( \theta = R/D_\Lambda(z) \),

\[
\langle T \rangle = \int_{\Delta \theta} \delta T(\delta) e^{-\delta^2/[2\sigma(R)^2]} \, d\delta
\]

(8)

Here

\[
\langle T \rangle = \frac{1}{2\pi\sigma(R)} \int \delta T(\delta) e^{-\delta^2/[2\sigma(R)^2]} \, d\delta
\]

and \( \theta = R/D_\Lambda \), where \( D_\Lambda \) is the angular diameter distance. The autocorrelation function of 21-cm brightness temperature within spheres of observed radius \( \theta \) is plotted in the lower left-hand panel of Fig. 1.

We also compute the autocorrelation function \( \langle \xi_{SF}^2(\theta) \rangle \) of fluctuations in Lyα emission \( \Gamma \) smoothed with top-hat windows of angular radius \( \theta = R/D_\Lambda(z) \),

\[
\langle \Gamma \rangle = \left( \langle \xi_{SF}^2(\theta) \rangle \right)^{1/2}
\]

(9)

\[
\langle \Gamma \rangle = \left( \frac{1}{2\pi\sigma(R)} \int \delta \Gamma(\delta) e^{-\delta^2/[2\sigma(R)^2]} \, d\delta \right)^{1/2}
\]

(10)

\[
\langle \Gamma \rangle = \frac{1}{\sqrt{2\pi\sigma(R)}} \int \delta \Gamma(\delta) e^{-\delta^2/[2\sigma(R)^2]} \, d\delta
\]

Figure 1. Upper left-hand panel: The luminosity density [erg s\(^{-1}\) (comoving Mpc\(^{-1}\)] in the Lyα line as a function of the large-scale overdensity (\( \delta \)). Upper right-hand panel: The cross-correlation function (at zero lag) of the luminosity density in the Lyα line, with the 21-cm brightness temperature contrast within spheres of observed radius \( \theta \). Lower left-hand panel: The autocorrelation function of 21-cm brightness temperature within spheres of observed radius \( \theta \). Lower right-hand panel: The autocorrelation function of luminosity density in the Lyα line within spheres of observed radius \( \theta \).
Correlation of star formation and 21-cm emission

7 THE CROSS-CORRELATION BETWEEN Lyα AND 21-cm EMISSION

The properties of the galaxy population are expected to correlate with the level of redshifted 21-cm emission. These properties depend on the overdensity of the IGM whose typical fluctuation level is a function of scale. As a result, the amplitude of the correlation between fluctuations in Lyα emission \((\Gamma - \langle \Gamma \rangle)\) and fluctuations in 21-cm brightness temperature contrast \((T - \langle T \rangle)\) will therefore also be dependent on angular scale. On a comoving scale \(R\) larger than the characteristic bubble radius, we are able to compute the cross-correlation function at zero lag between Lyα and 21-cm emission:

\[
\xi_{T,\alpha}(\theta) = \langle (\Gamma - \langle \Gamma \rangle)(T - \langle T \rangle) \rangle \approx \frac{1}{\sqrt{2\pi\sigma(T)}} \int d\delta \Gamma(\delta)e^{-\delta^2/(2\sigma(R)^2)},
\]

for the IGM smoothed on various angular scales. The resulting amplitude of cross-correlation of the luminosity density in the Lyα line, with the 21-cm brightness temperature contrast within spheres of observed radius \(\theta\) is shown in the top right-hand panel of Fig. 1.

The sign of this cross-correlation is negative, indicating an anticorrelation between star formation and 21-cm emission. This anticorrelation arises as a result of the higher star formation rates generated due to galaxy bias in overdense regions, which are therefore reionized first. The amplitude of the cross-correlation decreases towards large scales.

Before proceeding we note that we limit our analysis to correlation and cross-correlation functions computed at zero lag. However as pointed out recently by Barkana (2007), additional information may be obtained by considering the full correlation functions rather than just the modes of the fluctuations around single points. The analysis presented here could similarly be extended to compute the real-space correlation and cross-correlation functions.

8 DETECTABILITY OF THE CROSS-CORRELATION SIGNAL

In the remainder of this paper we discuss detection of the predicted cross-correlation between Lyα and the 21-cm emission. We begin with the Lyα signal and extragalactic foreground, which we assume are measured in a wide-field near-IR survey through a narrow-band filter centred on the redshifted Lyα wavelength. We then discuss the sensitivity of planned low-frequency arrays to the redshifted 21-cm signal, before describing prospects for detection of the predicted cross-correlation between Lyα and redshifted 21-cm emission using a range of current and future observational facilities.

8.1 The Lyα flux

Equation (8) can be used to compute the fluctuations in Lyα luminosity from spherical regions subtending an angle \(\theta\),

\[
\Delta L_{\alpha} = (\xi_{T,\alpha})^{1/2} \frac{4\pi(\theta D_{\alpha})^3}{3},
\]

while the corresponding total luminosity follows from equation (5):

\[
L_{\alpha} = \langle \frac{4\pi(\theta D_{\alpha})^3}{3} \rangle.
\]

For a telescope of diameter \(d\), the fluctuations in the observed photon count are given by

\[
\Delta N_{\alpha} = \pi \left( \frac{d}{2} \right)^2 \Delta L_{\alpha} \frac{1}{4\pi D_{\alpha}^2 h \nu_{\text{obs}}}.
\]

where \(D_{\alpha}\) is the luminosity distance and \(\nu_{\text{obs}}\) is the observed frequency of the Lyα photons. Similarly, the total flux in Lyα photons is

\[
N_{\alpha} = \pi \left( \frac{d}{2} \right)^2 \frac{L_{\alpha}}{4\pi D_{\alpha}^2 h \nu_{\text{obs}}}.
\]

Fig. 2 shows the observed fluxes and fluctuations in observed fluxes in units of photons per hour. In Fig. 2 we assumed a 2-m telescope.
with a 1-h integration time. The large black dots and thin solid line refer, respectively, to the fluctuation level ($\Delta N_{fg}$) and the total level ($N_{fg}$) of Lyα emission within a spherical region of observed radius $\theta$.

### 8.2 Foreground emission

Observations through a narrow filter will detect fluctuations in Lyα emission superimposed on fluctuations in the extragalactic foreground. To estimate the importance of the foreground with respect to measurement of the cross-correlation we therefore need to estimate both the total foreground flux ($F$), and the fluctuations in total flux that enters the detector from a cone of angular radius $\theta$ at a frequency $\nu_{\text{obs}}$. For our purposes it is sufficient to estimate the foreground flux using the following simple model:

$$F(\theta, \nu_{\text{obs}}) = \int \frac{d\nu}{d\Omega} \pi D_L(z) c \frac{d^2E}{d\Omega d\nu} \bigg|_{\nu = \nu_{\text{obs}}(1+z)} (1+z) \frac{4\pi D_L^2}{3},$$

where

$$\frac{d^2E}{d\Omega d\nu} = f_{\nu} \frac{\Omega_{\text{obs}}}{\Omega_{\text{lim}}} (1+z)^{1/2} \frac{dF_{\text{col}}}{d\nu} \frac{d^2E}{dM d\nu}$$

is the luminosity density. In the latter expression, $d^2E/dM d\nu$ is the luminosity produced at frequency $\nu$ per unit star formation rate. We assume a 1/20th solar metallicity population with a Scalo (1998) mass function, and use the stellar population model of Leitherer et al. (1999) to compute the spectrum of a continuously star-forming galaxy. For a narrow filter of width $\Delta \nu_{\text{obs}}$, the flux can then be converted into a photon detection rate,

$$N_{fg} = \frac{\pi}{2} \frac{F(\theta, \nu_{\text{obs}})}{h_{\nu_{\text{obs}}}} \Delta \nu_{\text{obs}},$$

where $h_{\nu}$ is Planck’s constant. The thin-dashed curve in Fig. 2 corresponds to the flux in a 100-Å band due to foregrounds at the wavelength of the observed Lyα emission from galaxies at $z = 7$. This model can be compared to the measured extragalactic foreground at 5000 Å. Bernstein, Freedman & Madore (2002) find flux at a level of $(1.2-3) \times 10^{-9}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ Sr$^{-1}$. In the units of Fig. 2, this observation is shown as the grey band. Our model estimate lies on the lower boundary of the measured range for the observed foreground.

There will be fluctuations ($\Delta N_{fg}$) in $N_{fg}$ among different lines of sight due to Poisson noise in the number of galaxies contributing to the foreground. The level of fluctuations is given by

$$\frac{\Delta N_{fg}}{N_{fg}} = \sqrt{\int_0^{1+z} dz \int_{M_{\text{lim}}}^{M_{\text{max}}} dM \epsilon g_{\text{fg}} \frac{dN}{dz} \frac{d\epsilon}{dM} \frac{d^2E}{d\nu dM} \bigg|_{\nu = \nu_{\text{obs}}(1+z)} (1+z) \frac{4\pi D_L^2}{3}},$$

where $N'(M, z)$ is the observed flux from a galaxy of mass $M$ at redshift $z$, and $\epsilon_g$ is the duty cycle. The presence of bright, resolved galaxies at low redshift increase the fluctuations in the smoothed foreground. To reduce the amplitude of fluctuations in the foreground, these resolved galaxies need to be removed. To estimate the foreground fluctuations in the absence of resolved galaxies, we therefore compute the flux corresponding to a photon-limited signal-to-noise ratio (S/N) of 30, given an assumed telescope diameter.

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1 Model spectra of star-forming galaxies obtained from http://www.stsci.edu/science/starburst99/.

2 Note that the flux levels of the foreground and the Lyα signal shown in Fig. 2 have different power-law dependences on $\theta$. This is because the foreground has been calculated in a cone, while the Lyα emission has been calculated in spheres.
in time and space can be removed through dithering techniques to produce a foreground free, and flattened field containing only the differential fluctuations in the signal (plus extragalactic foregrounds). However, the field can only be flattened to a finite fractional level (e.g. 0.01), which we define to be \( f_{\text{flat}} \). Observations will therefore contain an additional fluctuating term with an amplitude of \( \sigma_{\text{flat}} = f_{\text{flat}}(N + N_{\text{fg}} + N_{\text{sky}} + N_{\text{zodiacal}}) \). We will find that this term dominates the error budget on angular scales greater than a few arcminutes, and in the case of ground-based observations, that it will prevent detection of the cross-correlation on those scales.

8.4 Sensitivity to the 21-cm signal

In this section we discuss the response of a radio interferometer to the brightness temperature contrast of the 21-cm emission from the IGM. We define the error in brightness temperature per synthesized beam to be \( \sigma_T \). Assuming that calibration can be performed ideally, and that redshifted 21-cm foreground subtraction is perfect, the r.m.s. fluctuations in brightness temperature are given by the radiometer equation:

\[
\sigma_T = \frac{\epsilon \lambda^2 T_{\text{sys}}}{A_{\text{int}} \Omega_\nu \sqrt{t_{\text{int}} \Delta v_{21}}}.
\]

(21)

where \( \lambda \) is the wavelength, \( T_{\text{sys}} \) is the system temperature, \( A_{\text{int}} \) the collecting area, \( \Omega_\nu \) the effective solid angle of the synthesized beam in radians, \( t_{\text{int}} \) is the integration time, \( \Delta v_{21} \) is the size of the frequency bin and \( \epsilon \) is a constant that describes the overall efficiency of the telescope. We optimistically adopt \( \epsilon = 1 \) in this paper. In units relevant for upcoming telescopes and at \( \nu = 200 \) MHz, we find (Wyithe, Loeb & Barnes 2005)

\[
\sigma_T = 7.5 \text{mK} \left( \frac{1.97}{C_{\text{beam}}} \right) \left( \frac{A_{\text{int}}}{A_{\text{MWA}}} \right)^{-1} \left( \frac{\Delta v_{21}}{1 \text{ MHz}} \right)^{-1/2} \left( \frac{t_{\text{int}}}{100 \text{ h}} \right)^{-1} \left( \frac{\theta_{\text{beam}}}{5 \text{ arcmin}} \right)^{-2}.
\]

(22)

The label MWA corresponds to the Mileura Wide-field Array (see http://www.haystack.mit.edu/ast/arrays/mwa/site/index.html). \( A_{\text{MWA}} \) is the collecting area of a radio interferometer consisting of 500 tiles each with 16 phased cross-dipoles [the effective collecting area of an MWA tile with \( 4 \times 4 \) cross-dipole array with 1.07-m spacing is \( \sim 17-19 \) m\(^2\) between 100 and 200 MHz (B. Correy, private communication)]. The system temperature at 200 MHz will be dominated by the sky and has a value \( T_{\text{sys}} \sim 250 \) K. The size of the synthesized beam \( \theta_{\text{beam}} \) can be regarded as the radius of a hypothetical top-hat beam, or as the variance of a hypothetical Gaussian beam. The corresponding values of the constant \( C_{\text{beam}} \) are 1 and 1.97, respectively.

8.5 Estimate of S/N in detection of the cross-correlation

The observed cross-correlation function at zero lag \( \langle \xi_{\text{xy}} \rangle \) is a combination of real fluctuations and noise, hence we can write

\[
\xi_{\text{xy}}^{\text{obs}} = \langle \Delta N_{\text{xy}} \rangle + \sigma_{\text{fg}} + \sigma_{\text{sys}} (\Delta T + \sigma_T)
\]

(23)

\[
= \xi_{\text{xy}} + \langle \Delta N_{\text{xy}} \rangle + \langle \Delta N \Delta T \rangle + \langle \sigma_T \Delta T \rangle + \langle \sigma_{\text{fg}} \rangle + \langle \sigma_{\text{sys}} \Delta T \rangle + \langle \sigma_{\text{sys}} \sigma_T \rangle.
\]

Here we have assumed prior removal of spectrally smooth foreground from the redshifted 21-cm maps (this removal is expected to be part of the real-time data processing pipeline for an instrument like the MWA). We have also defined \( \Delta T = T - \langle T \rangle \). The fluctuations and noise in the foreground should be uncorrelated with the 21-cm signal. Similarly, the noise in the 21-cm signal should be uncorrelated with each of the Ly\(\alpha \) fluctuations, the noise in Ly\(\alpha \) flux, and the level of foreground. Terms 2–8 in the above equation therefore average individually to zero over a large sample. However for a finite sample, the expectation value will have a distribution with a finite variance about zero. To examine the variance, consider two variables \( x \) and \( y \). Their product has a distribution \( p(xy) \) with variance \( \sigma_{xy} \). If we sample this distribution \( N_{\text{points}} \) times, the resulting mean is distributed about zero with a variance \( \langle xy \rangle = \sigma_{xy} / \sqrt{N_{\text{points}}} \). Since 21-cm surveys are inherently wide field, the number of independent terms in the cross-correlation will be limited by optical surveys. The width of the frequency bin \( \Delta v_{21} \) corresponds to the line-of-sight depth of a spherical region of radius \( \theta \). At small angles this depth can be smaller than the line-of-sight distance corresponding to a narrow (100 Å) near-IR band. Thus if a map of Ly\(\alpha \) emission has an area \( A_{\text{sky}} \), then the number of regions is

\[
N_{\text{points}} \sim \frac{A_{\text{sky}}}{\theta^2} \left( \frac{\Delta v_{21}}{\nu_{21}} \right) \left( \frac{\nu_{21}}{v_1 + v_2} \right),
\]

(24)

where \( v_1 \) and \( v_2 \) are the redshifted frequencies of the 21-cm and Ly\(\alpha \) emission, respectively.

Fig. 3 shows each of the noise terms in equation (23) as a function of \( \theta \), corresponding to the case of an Ly\(\alpha \) survey with an area of \( A_{\text{sky}} \sim 10 \text{ deg}^2 \) flattened at the 1 per cent level \( (f_{\text{flat}} = 0.01) \), with

**Figure 3.** The signal and noise terms in equation (23) as a function of \( \theta \). This example assumed an Ly\(\alpha \) survey with an area of \( A = 100 \text{ deg}^2 \) using a 2-m space-based telescope and 1-h integration per pointing, combined with a low-frequency array of collecting area 10 times the MWA with an integration time of 1000 h. The near-IR observations were assumed to be flattened at the 1 per cent level.
an MWA integration time of 1000 h. Also shown is the expected cross-correlation function at zero lag (large dots). In the case shown, the cross-correlation would be only marginally detectable. The figure demonstrates that at large angular scales the detection is limited by the flatness of the Ly$\alpha$ field achieved in the experiment. At small angular scales the detection is limited by the error in the brightness temperature of a synthesized 21-cm beam. Improved measurements would therefore require flatter fields and larger radio arrays rather than deeper near-IR imaging.

The S/N for detection of the cross-correlation is given by

$$\left(\frac{S}{N}\right)^2 = \frac{(\xi_{\alpha \theta})^2}{\Sigma^2},$$

where

$$\Sigma^2 = (\Delta N_{\alpha \theta} \sigma_T)^2 + (\Delta N \Delta T)^2 + (\Delta N \sigma_T)^2 + (\Delta T \sigma_T)^2 + (\sigma_{\text{flat}} \sigma_T)^2.$$

S/N values as a function of angle are plotted in Fig. 4 assuming $f_{\text{flat}}$ is listed in each case. We have shown examples with values of $f_{\text{flat}}$ that are an order of magnitude smaller for ground-based examples. The upper row with $f_{\text{flat}} = 0$ represents an experiment with a perfectly flat near-IR image field.

Fig. 4 shows that the cross-correlation will be detectable at angles below a few arcminutes using wide-field space-based imaging ($\sim 100$ deg$^2$) combined with 10 times the MWA, provided that the Ly$\alpha$ images can be flattened at the $\sim 0.1$ per cent level. Ground-based studies will be limited by the flatness of the near-IR imaging field, and would need to reach values of $f_{\text{flat}} \sim 10^{-4}$ over 100 deg$^2$. At large angles the S/N is limited by the value of $f_{\text{flat}}$, and by the area of the survey. However, at small angles the measurement of cross-correlation is limited by the noise in the 21-cm observations, and so the S/N is proportional to collecting area of the low-frequency array. The greater sensitivity of a SKA therefore increases the S/N of the detection on scales near an arcminute. For example, an S/N greater

http://www.skatelescope.org/. The left- and right-hand panels correspond to space-based (i.e. no atmospheric sky glow, but including zodiacal light), and ground-based (i.e. including sky glow) imaging. The 2-m space-based telescope capable of wide-field imaging might represent a telescope like the planned Supernova Acceleration Probe (SNAP). The value of $f_{\text{flat}}$ (ranging between 0 and 0.01) is listed in each case. We have shown examples with values of $f_{\text{flat}}$ that are an order of magnitude smaller for ground-based examples. The upper row with $f_{\text{flat}} = 0$ represents an experiment with a perfectly flat near-IR image field.

The S/N for detection of the cross-correlation is given by

$$\left(\frac{S}{N}\right)^2 = \frac{(\xi_{\alpha \theta})^2}{\Sigma^2},$$

where

$$\Sigma^2 = (\Delta N_{\alpha \theta} \sigma_T)^2 + (\Delta N \Delta T)^2 + (\Delta N \sigma_T)^2 + (\Delta T \sigma_T)^2 + (\sigma_{\text{flat}} \sigma_T)^2.$$
The S/N results presented thus far have assumed that the sky glow and zodiacal light leave an imprint on the measured fluctuations via the instrumental effect of an imperfect flat-field. However, zodiacal light has very small spatial and temporal fluctuations (Kashlinsky et al. 2007). In space-based observations, the fluctuations introduced by variable instrumental response to the zodiacal glow and zodiacal light leave an imprint on the measured fluctuations due to imperfections in the flatness of the field are removed via subtraction of the constant foreground which is dominated by zodiacal light. However, this contribution is \(~\sim\)100 times smaller than the contribution from zodiacal light and we ignore it for this calculation.

The S/N results presented thus far have assumed that the sky

\[ S/N = \frac{\langle \Delta N \Delta T \rangle}{\sigma_{\Delta N} \sigma_{\Delta T}}. \]  

(27)

S/N values as a function of angle are plotted in Fig. 5 assuming parameters corresponding to a range of observational facilities. As before, all cases are shown, corresponding to Lyα surveys with areas of \( A_{\text{MW}} = 10 \) and 100 deg² performed using a 2-m telescope with 1-h integrations; combined with low-frequency arrays of collecting area corresponding to 1, 10 and 100 MWAs with an integration time 1000 h. Only one panel is shown because only space-based observations have been considered, and because the S/N calculated using equation (29) is not dependent on the parameter \( f_{\text{flat}} \).

Fig. 5 shows that at angles below a few arcminutes, the cross-correlation will be detectable using space-based wide-field imaging \((\sim 10 \text{deg}^2)\) combined with a low-frequency array of collecting area of at least 10 times that of the MWA. At large scales the S/N is substantially improved relative to Fig. 4. Fig. 5 shows that space-based near-IR surveys with areas of 100 deg² could achieve S/N \(~\sim\)5 on angles of 5–10 arcmin when combined with the MWA.

In principle, the removal of atmospheric sky glow could also be accomplished through subtraction of independent regions of sky in analogy to equations (27)–(29). However, since (unlike the zodiacal light) the atmospheric sky glow is variable on short time-scales, the removal would need to be averaged over a large number of pointings. We have not attempted to compute the S/N for a detection in this case.

9 DISCUSSION

Standard models for stellar reionization of the IGM predict a clear anticorrelation between the distribution of bright resolved galaxies and the 21-cm signal (e.g. Wyithe & Loeb 2007). Moreover this anticorrelation would be easily detectable (Furlanetto & Lidz 2007; Wyithe & Loeb 2007). However, reionization is thought to be dominated by low-mass galaxies. In this paper we have demonstrated that the cross-correlation between fluctuations in the surface brightness of Lyα emission (as a proxy for star formation rate) and the redshifted 21-cm signal, will directly test the existence of a causal link between the production of ionizing photons by stars and the reionization of the IGM.
The faint galaxies that make up the unresolved component of high-redshift emission produce most of the Lyα emission (and corresponding UV radiation). One might therefore suppose that it should be easier to detect the correlation between the unresolved component and the 21-cm emission. However (once a redshift is measured), fluctuations in the resolved galaxy distribution do not suffer from extragalactic foreground or sky brightness contamination, while the unresolved emission must be separated from the fluctuating foreground statistically based on its cross-correlation with the 21-cm signal. The correlation of the 21-cm signal with a fluctuating Lyα surface brightness will therefore be substantially more difficult to detect than a correlation with resolved galaxies (Furlanetto & Lidz 2007; Wyithe & Loeb 2007).

In this paper we have assumed that measurement of the cross-correlation between 21-cm intensity and diffuse Lyα emission would be performed using observations in a narrow near-IR band. The advantage of a narrow-band is that the relative fluctuations in both Lyα and 21-cm emission are larger than they would be if averaged over a wider line-of-sight interval, corresponding to a broad-band. On the other hand, the S/N in an individual pointing is increased if a broad-band is used, making detection of the smaller fluctuations easier. The key ingredient to measuring the fluctuations due to star formation at high redshift is the ability to remove fluctuations due to the foreground galaxies. As we have shown, these fluctuations are comparable in magnitude to the Lyα signal. Existing measurements of fluctuations in unresolved emission have required subtraction of an estimated fluctuating foreground component (Kashlinsky et al. 2005). Here we suggest removal of the foreground fluctuations statistically using the fact that these are uncorrelated with the redshifted 21-cm emission. The 21-cm emission also has a fluctuating foreground, and this foreground will be correlated with the foreground in the Lyα observations. It is proposed as part of upcoming 21-cm experiments, that this redshifted 21-cm foreground be removed using the smoothness of the spectrum of foreground sources (which will be compared with the rapid frequency fluctuations of the 21-cm signal). Since the radio and Lyα flux are both generated by foreground galaxies it is possible that these could positively cross-correlate. The foreground removal will therefore need to be very accurate in order for a negative cross-correlation to be detected. The proposed foreground subtraction methods will reveal the narrow-band 21-cm fluctuations, but will not allow detection of broad-band fluctuations. Hence a narrow-band near-IR observation would be the optimal choice for detecting the cross-correlation between the Lyα and 21-cm signals.

A measurement of the expected anticorrelation between the local star formation rate and the ionization state of the IGM, would provide crucial evidence in favour of a model in which stars reionized the Universe over alternative models in which reionization resulted from decaying particles (Hansen & Haiman 2004; Biermann & Kusenko 2006; Kasuya & Kawasaki 2007; Ripamonti et al. 2007) or from a more diffuse X-ray background (Madau et al. 2004; Ricotti et al. 2005). Alternatively, the detection of a positive cross-correlation would argue strongly against stellar sources of reionization, provided that the possibility that the radio foregrounds are providing the cross-correlation could be excluded.

We have analysed the prospects for detection of the predicted cross-correlation between Lyα and 21-cm emission, and found that detection will be possible at angular scales smaller than ∼10 arcmin. At scales of 5–10 arcmin the measurement could be performed using near-IR imaging from space, combined with a low-frequency array having a collecting area equal to that of the MWA. At smaller angular scales the S/N can be significantly increased, but will require a collecting area for redshifted 21-cm observations of at least 10 times the MWA. Observations from the ground will be limited by the difficulties of subtracting a sufficiently flat sky, which would be dominated by atmospheric sky glow. When 21-cm observations are combined with space-based near-IR imaging, the detection on scales smaller than a few arcminutes will be limited by the sensitivity to the 21-cm signal. This will be true even when the experiment is performed with a small-aperture optical telescope over a moderate field of view (∼10 deg²).

A futuristic wide-field space-based survey telescope combined with a square kilometre array would detect the cross-correlation at very high S/N values over a range of angular scales below a few arcminutes. The space-based near-IR survey need not have a very highly sampled point spread function beyond that necessary for the subtraction of resolved galaxies. A space-based survey telescope like the proposed SNAP would therefore provide the ideal facility with which to explore the connection between star formation and the reionization of the universe. To perform an experiment of the sort proposed in this paper, the survey telescope would need to carry an appropriate narrow-band filter. To study star formation at z ∼ 7, corresponding to the examples presented in this paper the filter should be centred at a wavelength of ∼9700 Å with a width of ∼100 Å.

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