Non-gravitational contributions to the clustering of Lyα selected galaxies: implications for cosmological surveys

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\textbf{ABSTRACT}

We show that the dependence of Lyα absorption on environment leads to significant non-gravitational features in the redshift space power spectrum of Lyα selected galaxies. We derive a physically motivated fitting formula that can be included in clustering analyses, and use this to discuss the predicted features in the Lyα galaxy power spectrum based on detailed models in which Lyα absorption is influenced by gas infall and/or by strong galactic outflows. We show that power-spectrum measurements could be used to study the astrophysics of the galaxy–intergalactic medium (IGM) connection, and to measure the properties of outflows from star-forming galaxies. Applying the modified redshift space power spectrum to a Lyα survey with parameters corresponding to the planned Hobby–Eberly Telescope Dark Energy Experiment (HETDEX), we find that the dependence of observed Lyα flux on velocity gradient and ionizing background may compromise the ability of Lyα selected galaxy redshift surveys to constrain cosmology using information from the full power spectrum. This is because the effects of fluctuating ionizing background and velocity gradients affect the shape of the observed power spectrum in ways that are similar to the shape of the primordial power spectrum and redshift space distortions, respectively. We use the Alcock–Paczynski test to show that without prior knowledge of the details of Lyα absorption in the IGM, the precision of line of sight and transverse distance measurements for HETDEX will be ∼1.3–1.7 per cent, decreased by a factor of ∼1.5–2 relative to the best case precision of ∼0.8 per cent available in a traditional galaxy redshift survey. We specify the precision with which modelling of Lyα radiative transfer must be understood in order for HETDEX to achieve distance measurements that are better than 1 per cent.

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

1 INTRODUCTION

The Lyα emission line of galaxies provides a primary observable for discovering high-redshift galaxies (e.g. Iye et al. 2006; Kashikawa et al. 2006; Lehnert et al. 2010; Ouchi et al. 2010) for studying their star formation and interstellar medium (ISM; e.g. Verhamme, Schaerer & Maselli 2006; Dessauges-Zavadsky et al. 2010; Steidel et al. 2011), and for studying the ionization state of the intergalactic medium (IGM; e.g. Haiman & Spaans 1999; Malhotra & Rhoads 2004; Kashikawa et al. 2006; Dijkstra, Wyithe & Haiman 2007b). In addition to measuring the luminosity function of Lyα emitting galaxies (e.g. Kashikawa et al. 2006; Shimasaku et al. 2006; Ouchi et al. 2008, 2010; Blanc et al. 2010; Cassata et al. 2011), samples have recently become large enough to enable studies of Lyα galaxy clustering (e.g. Gawiser et al. 2007; Kovač et al. 2007; Orsi et al. 2008; Guaita et al. 2010; Ouchi et al. 2010). These clustering studies yield complementary information to the luminosity function, since clustering of galaxies can provide a direct estimate of the halo mass, independent of the lifetime of starburst activity. Comparison with the luminosity function therefore provides an avenue to estimate the overall efficiency and duration of star-formation activity (e.g. Nagamine et al. 2010).

Unlike populations of Lyman-break galaxies that are selected via broad-band photometry, the observed brightness of a Lyα emitter is sensitive to its local extragalactic environment. In particular, Lyα radiation that escapes from galaxies can be scattered out of the line of sight by neutral hydrogen atoms in IGM surrounding the
For example, prior to the completion of reionization, the strength of the damping wing in the Lyα absorption line means that Lyα galaxies should be more easily detected inside the H I regions that are thought to have been generated by clustered early star-forming galaxies (e.g. Santos 2004; Wyithe & Loeb 2005; Mesinger & Furlanetto 2008a), leading to enhanced clustering that could provide a signature of patchy reionization (McQuinn et al. 2007; Iliev et al. 2008; Mesinger & Furlanetto 2008b).

Following the conclusion of reionization, the fraction of radiation that is scattered out of the line of sight is dependent on resonant absorption within the highly ionized IGM. In this regime, the fraction of Lyα flux that is transmitted to the observer is dependent on quantities like the infall velocity, the local overdensity of mass and the ionizing background. Any environmental dependence of observed flux at fixed intrinsic luminosity therefore leads to an environmental dependence of the host halo mass of observed galaxies at fixed observed flux. This in turn leads to a dependence of the observed galaxy density on environment that differs to that expected from galaxy bias. Since clustering studies are performed in flux-limited surveys, the net result is a modification of the observed clustering of Lyα selected galaxies (Zheng et al. 2011). This modification of the observed clustering is non-gravitational.

Galaxies are thought to provide a (biased) tracer of the density field, and hence their clustering can be used to infer the statistical properties of the mass–density field on the large scales that probe cosmology (e.g. Cole et al. 2005; Eisenstein et al. 2005; Percival et al. 2007; Okumura et al. 2008; Gaztanaga, Cabrè & Hui 2009; Reid et al. 2010). The gravitational contributions to this clustering can be studied analytically, providing qualitative interpretation of the observations (e.g. Sheth, Mo & Tormen 2001). However, the precision of modern galaxy redshift surveys has meant that N-body analyses are required to understand the observations in detail (e.g. Tinker, Weinberg & Zheng 2006; Eisenstein, Seo & White 2007; Seo et al. 2008). While gravitational effects are thought to be the only mechanism influencing clustering at an observable level in traditional galaxy redshift surveys, studies of clustering among Lyα selected galaxies will need to also include non-gravitational contributions. For example, the effect of peculiar velocity gradients on the observed clustering of Lyα selected galaxies will not be the same as in a usual galaxy redshift survey (Zheng et al. 2011). This is because both the observed luminosity and the observed redshift space density of the Lyα galaxies depend on velocity gradient.

Zheng et al. (2011) employed a numerical simulation and calculated the full radiative transfer of Lyα photons to study the clustering of Lyα selected galaxies at $z = 5.7$. They argue that the effect of velocity gradients leads to line-of-sight clustering that is suppressed, in contrast to the enhancement seen in traditional galaxy redshift surveys (e.g. Kaiser 1987; Peacock et al. 2001). In addition to identifying this new clustering effect, Zheng et al. (2011) argue that clustering will be enhanced transverse to the line of sight, leading to a clustering amplitude that is increased relative to expectations in the absence of Lyα transmission effects.

An important difference between the study of Zheng et al. (2011) and previous related works (e.g. Santos 2004; Dijkstra et al. 2007a; Orsi et al. 2008; Dayal et al. 2009) is the implementation of full radiative transfer within their simulation (Zheng et al. 2010). Many previous studies have utilized a model in which the fraction of Lyα photons that reach the observer is equal to $\exp(-\tau)$, where $\tau$ is the integrated Lyα optical depth along the line of sight. However, Zheng et al. (2011) argue that photons are scattered back into the line of sight along directions of low density, and so must be included in addition to the directly transmitted photons accounted for in the $\exp(-\tau)$ model. They argue that while the $\exp(-\tau)$ model provides a qualitative explanation of observed Lyα galaxy properties, quantitative differences are found which require full radiative transfer to interpret.

The issue is partially related to the size, and hence the surface brightness, of the region from which Lyα photons are scattered to the observer. This size is very sensitive to the properties of the gas within the virial radius of a galaxy, and also depends on the intrinsic broadness of the line (Laursen, Sommer-Larsen & Razoumov 2011). In a recent paper, Laursen et al. (2011) have modelled sightlines to galaxies at lower redshift and at much higher resolution than are available in the simulations of Zheng et al. (2010). In contrast to Zheng et al. (2011), Laursen et al. (2011) find that the $\exp(-\tau)$ model provides an excellent description of the fraction of transmitted flux that they compute from their high-resolution radiative transfer simulations. However, Laursen et al. (2011) are not able to study the effect of transmission on Lyα galaxy clustering.

We predominantly consider clustering of Lyα galaxies at $z \lesssim 3$. Following Laursen et al. (2011), we therefore employ an $\exp(-\tau)$ model for Lyα transmission, and use this to explore the possible effect of environmental dependence of Lyα transmission on the clustering of Lyα selected galaxies. This enables us to draw on the extensive prior work evaluating the possible effects of different astrophysical effects including infall and star formation rates (SFRs; Dijkstra, Lidz & Wyithe 2007a), and galactic winds and outflows (Ahn, Lee & Lee 2003; Verhamme et al. 2008; Dijkstra & Wyithe 2010). The detailed analytic models we use in this work are in agreement with the simulations of Laursen et al. (2011). Since we do not know the phenomena that are most important in setting the observed flux of Lyα emitting galaxies, the goal of this work is not to produce a detailed model for the Lyα luminosity function itself or to predict the clustering amplitude (e.g. Orsi et al. 2008; Shimizu, Yoshida & Okamoto 2011). Rather, we aim to understand the effect that fluctuations in transmission will have on the shape of the power spectrum as a function of scale and direction, as well as on the clustering amplitude.

Most studies of clustering among Lyα emitting galaxies at high redshift have concentrated on applications related to probing the history of reionization and the sources responsible for that event. However, recent attention has also focused on obtaining large samples of Lyα emitters to use as tracers of the density field (Hill et al. 2004, 2008), with application to cosmological distance measure and probes of dark energy at redshifts not previously studied (Hobby–Eberly Telescope Dark Energy Experiment, HETDEX). In this paper, we discuss the implications of non-gravitational contributions to the observed clustering of Lyα emitting galaxies for studies of the shape, amplitude and angular dependence of the Lyα galaxy power spectrum. To this end, we provide a simple framework that allows the influence of non-gravitational effects from Lyα transmission to be evaluated with respect to the available precision of cosmological constraints. As part of our study, we determine the detail with which the astrophysics governing the observed properties and flux of Lyα emitters must be understood, in order for a large survey like HETDEX to achieve its theoretical performance in measurement of cosmological parameters.

Our paper is set out as follows. In Section 2 we construct a linear theory model for the power spectrum of Lyα selected galaxies, which is generalized to be applicable to any particular model of Lyα transmission. We next discuss a simple analytic model of transmission (Section 3), in which a fraction $F$ of the Lyα line is subject to optical depth $\tau_\text{opt}$. We provide an analytic formula for the resulting redshift space and spherically averaged power spectra, which
we use to discuss the physical origin of different features in the power spectrum. In Section 4 we investigate the effect of transmission fluctuations on clustering using detailed, previously published models of Lyα transmission. Having determined the likely extent of non-gravitational contributions to the observed clustering, we present an analysis of the likely impact of possible fluctuations in Lyα transmission on the measurements of cosmological parameters in the HETDEX survey (Section 5). As a specific example, we compute the Alcock–Paczynski effect (Alcock & Paczynski 1979). In Section 6, we turn this analysis around and discuss the precision that will be available for constraints on Lyα transmission models. We present our conclusions in Section 7. In our numerical examples, we adopt the standard set of cosmological parameters (Komatsu et al. 2011), with values of Ωm = 0.27, Ωb = 0.05 and ΩΛ = 0.73 for the matter, baryon and dark energy fractional density respectively, and h = 0.70, for the dimensionless Hubble constant.

2 MODEL FOR THE CLUSTERING OF Lyα SELECTED GALAXIES

We begin by briefly summarizing the basic theory for absorption of Lyα photons from galaxies in the IGM, and then present a simple derivation of galaxy bias in linear theory. We use these as a basis to discuss the effects of fluctuations in the transmission of Lyα flux through the IGM on the observed clustering of Lyα emitters. Our derivation of fluctuations is similar to the analytic model presented in Zheng et al. (2011).

2.1 Lyα absorption in the IGM

The transmission of Lyα photons (e.g. Dijkstra et al. 2007a) is summarized briefly here to provide context for the new clustering calculations. The total opacity seen by a photon initially at frequency ν is

$$\tau(\nu) = \int_{r_{\text{vir}}}^{\infty} dr \, n_\text{HI}(r) x_H (\nu [1 + v_\nu(r)/c]) ,$$

(1)

where the Lyα absorption cross-section is written as σ_{Lyα}(\nu), and the gas at distance r greater than the virial radius r_{\text{vir}} has line-of-sight velocity v_\nu(r). The variable x_H is the fraction of hydrogen in atomic form, given at photoionization equilibrium in the optically thin limit by

$$x_H = \frac{n_\text{HI} \sigma_{\text{rec}}}{\Gamma} ,$$

(2)

where n_\text{HI} is the number density of hydrogen nuclei, Γ is the photoionization rate and σ_{\text{rec}} is the Case-B recombination coefficient, σ_{\text{rec}} = 4.2 \times 10^{-13} (T_{\text{gas}}/10^4 \text{ K})^{-0.7} \text{ cm}^3 \text{s}^{-1} (e.g. Hui & Gnedin 1997). Substituting, we find

$$\tau(\nu) = \int_{r_{\text{vir}}}^{\infty} dr \, \frac{n_\text{HI}(r) \sigma_{\text{rec}}}{\Gamma(\nu)} \sigma_{Lyα}(\nu [1 + v_\nu(r)/c]) .$$

(3)

The total transmission is found by integrating over the flux density J(\nu) in the Lyα line:

$$T = \int_{r_{\text{vir}}}^{\infty} \frac{d\nu}{J(\nu)} e^{-\tau(\nu)}.$$  

(4)

The lower limit to the line-of-sight integration in equation (1) is set to r_{\text{min}} = r_{\text{vir}}. To motivate this limit we note that at r < r_{\text{vir}} the gas is likely to be both quasi-static and shock-heated to the virial temperature of the halo, which, for the halo masses of interest (M_{\text{halo}} \gtrsim 10^{10} M_\odot) corresponds to T_{\text{vir}} \gtrsim 10^4 \text{ K}. At these temperatures, collisions keep this gas highly ionized and transparent to Lyα radiation. This picture is complicated by the colder (T \sim 10^3 \text{ K}) gas streams seen in hydrodynamical simulations of galaxy formation that can exist down to r \sim 0. However, the covering factor of this material is small (Faucher-Giguère & Kereš 2011). Photons that scatter at r > r_{\text{vir}} emerge as a low surface brightness ‘fuzz’, with an angular extent relative to the galaxy of θ \sim 3 (r_{\text{vir}}/r_{\text{fuzz}} 20 \text{ kpc}) arcsec. This value should be compared with observed Lyα emitters that are generally much more compact, indicating that scattered radiation is not detected.\footnote{Laursen et al. (2011) found that a fraction of the photons scattered back into the line of sight at r_{\text{fuzz}} < r < 1.5 r_{\text{vir}} are detectable, and that therefore ideally one should adopt r_{\text{min}} = 1.5 r_{\text{vir}}. This difference probably arises because Laursen et al. (2011) include lower mass haloes (M < 10^{10} M_\odot) in their analysis, for which the virial radius is smaller. However, the uncertainties due to the detailed choice of r_{\text{min}} are significantly less than those corresponding to the radiative transfer effects associated with galactic outflows.}

We study the transfer of Lyα photons through the ionized IGM. In this scenario, the opacity is completely dominated by hydrogen atoms for which the Lyα photons appear to be at line resonance. Approximating the Lyα scattering cross-section as a delta function σ_{Lyα}(\nu) \sim σ_{Lyα,\text{tot}}(\nu - ν_{Lyα}), where σ_{Lyα,\text{tot}} \equiv \int \sigma_{Lyα} d\nu = f_α(\pi e^2/m_e c) (Rybicki & Lightman 1979)^2 and ν_{Lyα} = ν[1 + v(r)/c], we can rewrite equation (3) as

$$\tau(\nu) \approx \int_{r_{\text{vir}}}^{\infty} dr \, \frac{n_\text{HI}(r) \sigma_{\text{rec}}}{\Gamma(\nu)} \sigma_{Lyα}(\nu - ν_{Lyα}) \left[ 1 + \frac{v_\nu(r)}{c} \right] ,$$

(5)

where ν_{Lyα} = ν[1 + v(r)/c], in which r_{Lyα} denotes the radius at which the photon is at resonance in the frame of the gas. Equation (5) illustrates the important point that the probability of Lyα scattering is proportional to the total number of hydrogens that the photon encounters per unit velocity along the line of sight. The optical depth is therefore proportional to the inverse of the line-of-sight velocity gradient (dv/dr)^{-1}, in addition to the more obvious dependencess of density squared and inverse of ionization rate. Thus we find

$$\tau \propto \frac{\rho^2}{\Gamma T^{0.7} \frac{dv}{dr}} \alpha \frac{\rho^{2-0.7}(\nu - 1)}{\Gamma^{10.7} \frac{dv}{dr}} ,$$

(6)

where in the second proportionality we have assumed a power-law relation between density and temperature of T \propto \rho^{\alpha-1}, with the polytropic index γ = 1.4 (Hui & Gnedin 1997). We note that the assumption of a delta function to represent the Lyα scattering cross-section is only used for illustration in equations (5–6). The modelling of Lyα transmission presented in this paper utilizes the full expression σ_{Lyα}(\nu) for the frequency dependence of Lyα scattering.

2.2 Galaxy bias and fluctuations in the number density of galaxies

The likelihood of observing a galaxy at a random location is proportional to the local number density of galaxies. The likelihood of observing a galaxy within a region of large-scale overdensity is therefore equal to the ratio of the number density of haloes n(δ) in a region of large-scale over-density δ to the number density of haloes in the background universe (n). This ratio has been used to derive galaxy bias for small values of δ (Mo & White 1996; Sheth et al.

\footnote{Here, f_{Lyα} = 0.4167 denotes the oscillator strength for the Lyα transition, and ε and m_e denote the charge and mass of the electron, respectively.}
where \( (\delta n/\delta M) \) and \( (\delta n/\delta M) (\nu) \) are the average and perturbed mass functions, \( \nu \equiv (\delta - 1.69)/\sigma(M) \), \( \sigma(M) \) is the variance in the density field smoothed on a mass scale \( M \) at redshift \( z \), and \( b \) is the bias factor. At small values of large-scale overdensity \( \delta' \), and in the absence of effects that influence the relation between observed flux and halo mass, the number density of galaxies is proportional to \( [1 + b \delta(M, z)] \).

2.3 The Ly\(\alpha\) emitter power spectrum

In this section we estimate the effect of transmission fluctuations on clustering of Ly\(\alpha\) selected galaxies, beginning with equations (6) and (7) as motivation. Fluctuations in transmission of Ly\(\alpha\) through the IGM modify the intrinsic luminosity that corresponds to an observed flux limit \( F_0 \). This modification of intrinsic luminosity in turn leads to a modification of number counts according to the luminosity function of Ly\(\alpha\) emitters.

The density \( n_{Ly}\alpha \) of Ly\(\alpha\) emitters that are observed with fluxes greater than \( F_0 \) [corresponding to an intrinsic luminosity \( L_0 \) with transmission \( T_0 = \exp(-\tau_0) \)] can then be expressed relative to the average \( n_{Ly}\alpha (L_0, \hat{r}_0, \nu_0) \) as

\[
\frac{n_{Ly}\alpha (L_0, \hat{r}_0, \nu_0)}{n_{Ly}\alpha (L_0, \hat{r}_0, \nu_0)} = \left[ \frac{\delta (\log T)}{\delta \log \nu} \right] \left[ \frac{\delta \hat{\sigma}_{Ly\alpha}}{\delta \nu} \right]_{T_0, \hat{r}_0, \nu_0} \right]_{T_0, \hat{r}_0, \nu_0} \right]_{T_0, \hat{r}_0, \nu_0} \right]
\]

where \( H \) is the Hubble parameter at scale factor \( a \), and \( \nu_{com} \) is a comoving distance. Here, \( n_{Ly}\alpha (L_0, \hat{r}_0, \nu_0) \) is the mean number density of Ly\(\alpha\) emitters with luminosities greater than \( L_0 \), and \( n_{Ly}\alpha (L_0, \hat{r}_0, \nu_0) \) is the perturbed number density of Ly\(\alpha\) emitters with observed fluxes greater than the corresponding \( F_0 \). We define the variable \( \delta_\nu \equiv \nu - \nu_0 \) as the fluctuation in the ionizing background (discussed further below). We introduce a change of coordinates \( \frac{\delta \nu}{\delta \nu_{com}} \equiv -H \), and define the symbol \( \delta_\nu \equiv \frac{\delta \nu}{\delta \nu_{com}} \), which represents the fluctuation in line-of-sight velocity. With these, we obtain:

\[
\frac{n_{Ly}\alpha (L_0, \hat{r}_0, \nu_0)}{n_{Ly}\alpha (L_0, \hat{r}_0, \nu_0)} = \left[ \frac{\delta (\log T)}{\delta \log \nu} \right] \left[ \frac{\delta \hat{\sigma}_{Ly\alpha}}{\delta \nu} \right]_{T_0, \hat{r}_0, \nu_0} \right]
\]

Rearranging, we get the fluctuation in the number density of Ly\(\alpha\) emitters:

\[
\delta_{Ly\alpha} = \frac{n_{Ly\alpha}}{n_{Ly\alpha}} - 1 = \delta (b + C_\rho) + \delta_\nu C_\nu + \delta_\nu C_\nu,
\]

where

\[
C_\rho = \frac{1}{n_{Ly\alpha}} \frac{\delta n(L)}{\delta \log L} \left. \frac{\partial (\log L)}{\partial \log \rho} \right|_{T_0, \hat{r}_0, \nu_0}
\]

(11)

\[
C_\nu = \frac{1}{n_{Ly\alpha}} \frac{\delta n(L)}{\delta \log L} \left. \frac{\partial (\log \nu)}{\partial \log \nu} \right|_{T_0, \hat{r}_0, \nu_0}
\]

(12)

and

\[
C_\nu = \frac{1}{n_{Ly\alpha}} \frac{\delta n(L)}{\delta \log \nu} \left. \frac{\partial (\log \nu)}{\partial \log \nu} \right|_{T_0, \hat{r}_0, \nu_0}
\]

(13)

By convolving the overdensity field of sources at points \( z_0 \) with a kernel \( \chi \exp [-((x - x_0)/\lambda)^2]/(x - x_0)^2 \), the Fourier component of the ionizing radiation field can be written (Morales & Wyithe 2010) as

\[
\delta_{\nu} = \frac{b_0}{k \lambda} \arctan \left( \frac{k \lambda}{\nu} \right),
\]

(14)

where \( \lambda \) is the ionizing photon mean free path. In redshift space, the fluctuation in the density of Ly\(\alpha\) galaxies is

\[
\delta_{Ly\alpha} = \delta_{Ly\alpha} - \frac{d \nu}{d \nu_{com}} \frac{1}{H \alpha} \equiv \delta_{Ly\alpha} - \delta_\nu.
\]

(15)

Combining equations (10), (14) and (15), the Fourier component of the fluctuation in space density of Ly\(\alpha\) emitters is then

\[
\delta_{Ly\alpha} = \delta_\nu \left[ \frac{b_0}{k \lambda} \right. \arctan \left( \frac{k \lambda}{\nu} \right) + C_\rho + (1 - C_\nu) f \mu^2
\]

(16)

where \( f = \frac{d \log \nu}{d \log \nu} - 1 \), \( \mu \) is the cosine of the angle between the line of sight and the wave vector for the Fourier mode of interest, and we have used the relation \( \delta_\nu = -f \mu^2 \delta_\nu \) relating fluctuations in velocity gradient and density. The power spectrum follows directly, yielding

\[
P_{Ly\alpha}(k, \mu) = P(k) \left[ (1 + C_T K_\lambda) + C_\nu + (1 - C_\nu) f \mu^2 \right]^2,
\]

(17)

where \( P(k) \) is the mass power spectrum, and we have defined

\[
K_\lambda = \frac{\arctan \left( \frac{k \lambda}{\nu} \right)}{k \lambda} - C_\nu.
\]

(18)

The spherically averaged power spectrum is

\[
P_{Ly\alpha}^{\text{sp}}(k) = P(k) \left[ (1 + C_T K_\lambda) + C_\nu + (1 - C_\nu) f \mu^2 \right]^2
\]

\[
+ \frac{2}{3} \left( b_0 + C_T K_\lambda + C_\nu \right) \left( 1 - C_\nu \right) \left( 1 - C_\nu \right)
\]

\[
+ \frac{1}{5} \left( 1 - C_\nu \right)^2 \mu^2
\]

\[
\left. \right|_{T_0, \hat{r}_0, \nu_0}
\]

(19)

We note that if \( C_T = C_\nu = 0 \) (indicating no effect from Ly\(\alpha\) transmission), we obtain

\[
P_{Ly\alpha}(k, \mu) = P_{\text{mass}}(k) \left[ b_0 + f \mu^2 \right]^2
\]

(20)

and

\[
P_{Ly\alpha}^{\text{sp}}(k) = P_{\text{mass}}(k) \left[ b_0^2 + \frac{2}{3} b_0 f + \frac{1}{5} f^2 \right]
\]

(21)

as expected in the standard case of galaxy clustering (Kaiser 1987).

\[
\begin{align*}
\delta_{Ly\alpha} & = \frac{n_{Ly\alpha}}{n_{Ly\alpha}} - 1 = \delta (b + C_\rho) + \delta_\nu C_\nu + \delta_\nu C_\nu, \\
\left. \frac{\partial \log L}{\partial \log \rho} \right|_{T_0, \hat{r}_0, \nu_0} & = \left. \frac{\partial \log \nu}{\partial \log \nu} \right|_{T_0, \hat{r}_0, \nu_0} \\
\left. \frac{\partial \log L}{\partial \log \nu} \right|_{T_0, \hat{r}_0, \nu_0} & = \left. \frac{\partial \log \nu}{\partial \log \nu} \right|_{T_0, \hat{r}_0, \nu_0}
\end{align*}
\]
3 Analytic Model for the Effect of Lyα Transmission on Clustering

In this section we present a simple parametrized model for the fluctuations in Lyα transmission, and use it to obtain analytic expressions for the constants \( C_\rho, C_T \) and \( C_v \), and hence for the power spectrum. The resulting analytic expression is instructive for elucidating the different important effects. In Section 4 we use previously published detailed models of the Lyα emitter transmission to calculate more physically motivated values for \( C_\rho, C_T \) and \( C_v \).

3.1 Simple model for \( C_\rho, C_T \) and \( C_v \)

We begin by assuming a model in which the intrinsic Lyα line of a galaxy is symmetric about the rest-frame Lyα wavelength. We assume the Lyα emitters to be located in an ionized IGM. We also assume that most absorption occurs in regions that are far enough from the galaxy that the ionization rate is dominated by the ionizing background, rather than by ionizing flux associated with star formation in the Lyα emitting galaxy. In the absence of peculiar velocities in the IGM that cause departure from the Hubble flow, the red side of the line is transmitted through the IGM while the blue side is subject to resonant absorption (e.g. Madau 1995; Hu et al. 2004). However infall of intergalactic gas on to massive galaxies leads to resonant absorption that can reach into the red side of the intrinsic line profile (e.g. Dijkstra et al. 2007a; Laursen et al. 2011, see Section 4.1). On the other hand, galactic outflows have the effect of redshifting the emerging Lyα line relative to the true velocity of the galaxy, which makes the Lyα photons more ‘immune’ to scattering in the IGM (see Section 4.2).

To maintain generality, we therefore assume that a fraction \( F \) of the line is subject to absorption in the IGM. As illustrated by equation (6), the transmission of Lyα flux is dependent on the overdensity \( \delta \), and on the ionizing background and velocity gradient fluctuations \( \delta_\tau \) and \( \delta_v \). The remaining fraction \( (1 - F) \) is assumed to reach the observer. We therefore have the following expression for the overall transmission of the Lyα line:

\[
T(\delta, \delta_\tau, \delta_v) = (1 - F) + F \exp \left[ -\tau_0 \frac{1 + \delta(2.7 - 0.7\gamma)}{1 + \delta_\tau + \delta_v} \right],
\]

where \( \tau_0 \) is the mean Lyα optical depth in the IGM as a whole. This model can describe a wide range of physical scenarios. The case in which the IGM suppresses only the blue half of the line corresponds to \( F = 0.5 \), while infalling intergalactic gas can result in \( F > 0.5 \). Conversely, scattering through galactic winds can cause \( F < 0.5 \).

To calculate \( C_\rho, C_T \) and \( C_v \), we first need an expression for \( \mathcal{N}(L) / \mathcal{D}(L) \). For this calculation, we assume that the luminosity function can be approximated as a power law in the range of luminosities \( L \) observed,

\[
\mathcal{N}(L) / \mathcal{D}(L) \sim L^{-\beta}.
\]

We then obtain

\[
\frac{d \mathcal{N}(L)}{d \log T} \bigg|_{L_0,T_0} = \frac{d \mathcal{N}(L)}{d \log L} \frac{d \log L}{d \log T} \bigg|_{L_0,T_0} = (\beta - 1) \frac{\tau_{\alpha,0}}{\mathcal{N}_{L_0,0}},
\]

where we have used the relation \( L = L_0 T_0 \) (i.e. constant observed flux \( F_0 \)). Utilizing

\[
\frac{d \log L}{d \log \rho} \bigg|_{L_0,T_0} = \frac{-F(2.7 - 0.7\gamma) \tau_{\alpha,0}}{(1 - F) + F e^{-\tau_{\alpha,0}}},
\]

we obtain

\[
C_\rho = (\beta - 1) \frac{(0.7\gamma - 2.7)F \tau_{\alpha,0}}{(1 - F) + F e^{-\tau_{\alpha,0}}},
\]

and

\[
C_T = C_v = (\beta - 1) \frac{F \tau_{\alpha,0}}{(1 - F) + F e^{-\tau_{\alpha,0}}},
\]

Putting these pieces together we write down an analytic estimate for the power spectrum of Lyα selected galaxies:

\[
P_{\text{Lyα}}(k, \mu) = P_m(k) \left[ b + f \mu^2 + C \left( b K_\alpha + (0.7\gamma - 2.7) - f \mu^2 \right) \right]^2,
\]

where

\[
C = \frac{(\beta - 1)F \tau_{\alpha,0}}{(1 - F) + F e^{-\tau_{\alpha,0}}},
\]

We also obtain the spherically averaged power spectrum:

\[
P_{\text{Lyα}}^{\text{sph}}(k) = P_m(k) \left[ b + C (b K_\alpha + (0.7\gamma - 2.7)) \right]^2 + \frac{2}{3} \left( b + C (b K_\alpha + (0.7\gamma - 2.7)) (1 - C) \right) f + \frac{1}{3} (1 - C)^2 f^2.
\]

3.2 Results for analytic model

Some examples of the predicted power spectrum of Lyα selected galaxies calculated using this analytic model are shown in Fig. 1. In each case, the short-dashed, solid and long-dashed lines refer to the predicted power spectrum assuming the analytic model for \( C_\rho, C_T \) and \( C_v \) with \( F = 0.1, 0.5 \) and 0.9, respectively. The power spectrum in the absence of transmission effects (i.e. \( C_\rho = C_T = C_v = 0 \)) is shown by the solid grey line. The upper subpanels in each case show the ratio of these curves, indicating the fractional contribution of transmission effects to Lyα emitter clustering. Three cases are presented in Fig. 1. In the left-hand column we show a source redshift of \( z = 5.5 \), and assume \( \tau_0 = 3 \) and \( \lambda = 100 \) cMpc (Bolton & Haehnelt 2007), with a luminosity function slope\(^4\) of \( \beta = 2 \). In the central column we show results for \( z = 3.0, \tau_0 = 1 \) and \( \lambda = 300 \) cMpc (Bolton & Haehnelt 2007), using the same luminosity function slope of \( \beta = 2 \). In the right-hand column we again show results for \( z = 3.0, \tau_0 = 1 \) and \( \lambda = 300 \) cMpc, but this time assume a steep luminosity function slope of \( \beta = 2.5 \). At each redshift, the simple analytic model predicts that fluctuations in transmission can lead to a factor of 2 difference or more in the power-spectrum amplitude. The effects are enhanced by a steep luminosity function, owing to the proportionality of the coefficients \( C_\rho, C_T \) and \( C_v \) to the factor \( (\beta - 1) \).

\(^4\) The faint end slope of the Lyα luminosity function is not well constrained, and may shallower than \( \beta = 2 \) (Ouchi et al. 2008). However, the Lyα emitters that will be used in the HETDEX survey will be comparable in luminosity to those in the sample of Ouchi et al. (2008). At these luminosities, the slope of the luminosity function is steeper than at the faint end.
3.3 Contributions to the clustering amplitude

We next calculate the different contributions to the power spectrum of Lyα selected galaxies using the analytic model. The case of \( z = 3.0, \tau_0 = 1 \) and \( \lambda = 300 \text{ cMpc} \), with luminosity function slope \( \beta = 2 \) is shown in Fig. 2. The short-dashed, solid and long-dashed lines refer to the predicted power spectrum assuming the analytic model in cases where contributions are included from \( C_\rho \), from \( C_\rho \) and \( C_\Gamma \), and from all of \( C_\rho \), \( C_\Gamma \) and \( C_\nu \), respectively. We assumed \( F = 0.9 \) to accentuate the dependencies. The clustering in the absence of transmission effects (i.e. \( C_\rho = C_\Gamma = C_\nu = 0 \)) is shown by the solid grey line. Also shown (upper subpanels) is the ratio of these curves, indicating the fractional contribution of transmission effects to Lyα emitter clustering. The assumed halo mass was \( 10^{11} \text{ M}_\odot \).

![Figure 1. Clustering of Lyα emitters in the simple analytic model. The left-hand, central and right-hand panels show the spherically averaged power spectra in cases with \((z, \tau_0, \lambda, \beta) = (5.5, 3, 100 \text{ Mpc}, 2), (z, \tau_0, \lambda, \beta) = (3.0, 1, 300 \text{ Mpc}, 2) \) and \((z, \tau_0, \lambda, \beta) = (3.0, 1, 300 \text{ Mpc}, 2.5) \). In each case, the short-dashed, solid and long-dashed lines refer to the predicted clustering assuming the analytic model for \( C_\rho \), \( C_\Gamma \) and \( C_\nu \) with \( F = 0.1, 0.5 \) and 0.9, respectively. The clustering in the absence of transmission effects (i.e. \( C_\rho = C_\Gamma = C_\nu = 0 \)) is shown by the solid grey line. Also shown (upper subpanels) is the ratio of these curves, indicating the fractional contribution of transmission effects to Lyα emitter clustering. The assumed halo mass was \( 10^{11} \text{ M}_\odot \).](https://academic.oup.com/mnras/article-abstract/415/4/3929/1750264)

![Figure 2. Contributions to the spherically averaged clustering of Lyα emitters in the simple analytic model. The case of \( z = 3.0, \tau_0 = 1 \) and \( \lambda = 300 \text{ cMpc} \), with \( \beta = 2 \) is shown. The short-dashed, solid and long-dashed lines refer to the predicted clustering assuming the analytic model where contributions are included from \( C_\rho \), from \( C_\rho \) and \( C_\Gamma \), and from all of \( C_\rho \), \( C_\Gamma \) and \( C_\nu \). We assumed \( F = 0.9 \) to accentuate the dependencies. The clustering in the absence of transmission effects (i.e. \( C_\rho = C_\Gamma = C_\nu = 0 \)) is shown by the solid grey line. Also shown (upper subpanels) is the ratio of these curves, indicating the fractional contribution of transmission effects to Lyα emitter clustering. The assumed halo mass was \( 10^{11} \text{ M}_\odot \).](https://academic.oup.com/mnras/article-abstract/415/4/3929/1750264)
3.4 Redshift space clustering Lyα galaxies

In this subsection we discuss the effect of the velocity structure in the IGM on the observed two-dimensional redshift space clustering of Lyα selected galaxies on large scales. In Fig. 3 we plot contours of the redshift space power spectrum as a function of the line of sight ($k_\parallel = k \sin \theta$) and transverse ($k_\perp = k \sqrt{1 - \mu^2}$) components of the wavenumber $k$. The left-hand panel shows the clustering in the absence of transmission effects (i.e. $C_\parallel = C_\perp = C_\alpha = 0$). The effect of infall in the linear regime (Kaiser 1987) is clearly seen at small values of $k$, resulting in a power-spectrum amplitude that is increased at large scales in the line-of-sight direction.

The central panel shows contours of the power spectrum for the cases of $(z, \tau_0, \lambda, \beta) = (3.0, 1, 300 \text{ Mpc}, 2)$ and $(z, \tau_0, \lambda, \beta) = (3.0, 1, 300 \text{ Mpc}, 2.5)$. The left-hand panel shows the clustering in the absence of transmission effects (i.e. $C_\parallel = C_\perp = C_\alpha = 0$). The effect of infall in the linear regime (Kaiser 1987) is clearly seen at small values of $k$, resulting in a power-spectrum amplitude that is increased at large scales in the line-of-sight direction.

The central panel shows contours of the power spectrum for the cases of $(z, \tau_0, \lambda, \beta) = (3.0, 1, 300 \text{ Mpc}, 2)$. We have assumed $F = 0.9$ and $M = 10^{11} \text{ M}_\odot$. The non-zero $C_\parallel$ term in this model counteracts the Kaiser (1987) effect, leading to more isotropic redshift space clustering on large scales. In the right-hand panel we show a more extreme model for the luminosity function with $(z, \tau_0, \lambda, \beta) = (3.0, 1, 300 \text{ Mpc}, 2.5)$. In this case $C_\parallel > 1$, and so the Kaiser (1987) effect is reversed, leading to suppressed clustering transverse to the line of sight (Zheng et al. 2011).

3.5 Coefficients in the analytic model

The coefficients in the analytic model are dependent on assumed values for $F$ and $\tau_0$. In Fig. 4 we plot contours of the coefficients $C_\parallel$ and $C_\perp$ (left-hand panel), $C_\alpha$ (central panel) and the mean transmission $T_0$ (right-hand panel), each calculated as a function of $F$ and $\tau_0$. Large values of the coefficients require large values of $F$, indicating that a significant fraction of the intrinsic Lyα line must be subject to absorption in order to influence the clustering of Lyα selected galaxies at a level that is of order unity.

It is interesting to ask what properties of the model are required to obtain clustering that is enhanced transverse to the line of sight as reported in the numerical simulations of Zheng et al. (2011). Inspection of equation (29) indicates that $C_\alpha > 1$ is required. Assuming a luminosity function with $\beta = 2$, this can be achieved with $F > 0.9$ and $\tau_0 \sim 2$–5, for which the transmission is $T_0 \sim 5$–20 per cent, in good agreement with the Lyα emitters discussed in Zheng et al. (2011). If the luminosity function is steeper, then the requirements on $F$ are less stringent. For $\beta = 2.5$, the coefficients are increased by a factor of $(\beta - 1) = 1.5$ so that $C_\alpha > 1$ is obtained for $F > 0.8$.

4 DETAILED MODELLING OF TRANSMISSION AND CLUSTERING OF LYα EMITTERS

The analytic model discussed in Section 3 is useful for investigating the qualitative dependencies of clustering in Lyα selected galaxies. However, a more detailed analysis is required to quantitatively predict the values of constants $C_\parallel$, $C_\perp$, and $C_\alpha$, which describe the modification of the power spectrum from that measured by a traditional galaxy redshift survey. In this section we describe calculation of $C_\parallel$, $C_\perp$, and $C_\alpha$ based on two previously published models of Lyα emission. These models explore, respectively, the effects of local star formation and IGM infall (Dijkstra et al. 2007a), and of galactic wind-driven outflows (Verhamme et al. 2008; Dijkstra & Wyithe 2010), on the transmission of the Lyα line through the circumgalactic IGM.

4.1 Modelling Lyα transmission in the presence of IGM infall and galactic ionizing flux

The model presented in this section is based on the work in Dijkstra et al. (2007a), to which the reader is referred for a full description of the calculations. The IGM transmission is calculated using a model for the IGM that accounts for clumping and infall. In this model, resonant absorption of Lyα photons by gas in the infall region (which extends out to several virial radii; see Barkana 2004) erases a significant fraction of the Lyα line flux at frequencies redwards of the Lyα resonance. Here, we briefly summarize the model’s main ingredients.

The Lyα flux from star-forming galaxies originates in the dense nebulae from which the stars form. Approximately two out of three (0.68) ionizing photons produced by O stars (which are absorbed in the nebulae) are converted into Lyα for Case-B recombination (Osterbrock 1989). The total intrinsic Lyα luminosity of a galaxy can then be estimated from

$$L_{\text{Ly}α} = 0.68 h v_\alpha (1 - f_{\text{esc}}) \dot{Q}_H,$$

where $h v_\alpha = 10.2 \text{ eV}$ is the energy of a Lyα photon, $\dot{Q}_H$ is total luminosity of ionizing photons, and $f_{\text{esc}}$ is the escape fraction of ionizing photons from the galaxy. Since $\dot{Q}_H$ depends on the number of O stars, its value is sensitive to the assumed initial mass function (IMF) and metallicity of the gas from which the stars form. Under the assumption of constant SFR, Schaerer (2003) has calculated $\dot{Q}_H$ for several different IMFs, and for a range of metallicities $Z$.
For the models in this subsection the shape of the intrinsic Lyα line is assumed to be Gaussian (see Section 4.2 for a discussion of models, where we assume different intrinsic spectral line shapes). For gas that is optically thin to Lyα photons, a reasonable choice for the standard deviation of this Gaussian emission line is $\sigma_\alpha \sim v_{\text{esc}}$, where $v_{\text{esc}}$ is the virial velocity of the host galaxy halo (Santos 2004; Dijkstra et al. 2007a). The assumption of optically thin gas is not likely to reflect the reality of star-forming galaxies. However, the resulting Gaussian line shape facilitates comparison with previous work (especially the clustering analysis of Zheng et al. 2011). Furthermore, our calculations provide very similar values for the overall transmitted fraction of Lyα photons through the IGM to those obtained by Laursen et al. (2011), who explicitly computed the Lyα line shape emerging from simulated galaxies.

Given a galaxy spectrum bluewards of the hydrogen ionization threshold ($\nu_{\text{HI}}$) of $J(\nu) \propto \nu^\alpha$, the photoionization rate at distance $r$ from the galaxy can be found from

$$\Gamma(r) = \Gamma_{bg} + \frac{\beta_1}{\beta_0 - 3} \frac{\sigma_\nu Q_{\text{HI}} f_{\text{esc}}}{4\pi r^2},$$

(34)

where $\Gamma_{bg}$ is the photoionization rate of the metagalactic background, and we have approximated the hydrogen photoionization cross-section as $\sigma_\nu(\nu) = \sigma_\nu(\nu/\nu_{\text{HI}})^\alpha$, with $\sigma_\nu = 6.3 \times 10^{-18}$ cm$^2$. In addition to the radial dependence of the photoionization rate, we also require the radial density ($\rho$) and velocity ($v$) profiles of the intergalactic gas surrounding objects of mass $M$ (Barkana 2004). Useful fitting formulae (Dijkstra et al. 2007a) for these are

$$\rho(r) = \begin{cases} 20\bar{\rho}(r/r_{\text{vir}})^{-1} & r < 10r_{\text{vir}} \\ \bar{\rho} & r \geq 10r_{\text{vir}} \end{cases},$$

(35)

and

$$v_{\text{manifest}}(r) = \begin{cases} -v_{\text{circ}} + \frac{\text{d}v_{\text{manifest}}}{\text{d}r} (r - r_{\text{vir}}) & r_{\text{vir}} < r < 10r_{\text{vir}} \\ H(z)r & r \geq 10r_{\text{vir}}. \end{cases}$$

(36)

where the velocity gradient $\text{d}v_{\text{manifest}}/\text{d}r = [10r_{\text{esc}}H(z) + v_{\text{manifest}}]r_0 v_{\text{esc}}$ was chosen to make $v(r)$ continuous. We evaluate the optical depth in this model using equation (4), which is also integrated over the probability distribution of density contrasts (Miralda-Escudé, Haehnelt & Rees 2000). The radial dependencies of $n_{\text{HI}}, \nu$ and $\Gamma$ in equation (4) are specified by equations (34–36).

For our calculations, we assume an IGM temperature of $T = 2 \times 10^4$ K (e.g. Lidz et al. 2010), consider a halo mass of $M = 10^{11}\ M_\odot$ (Orsi et al. 2008; Guaita et al. 2010), and a SFR of $M_\odot = 10^{0.3}\ M_\odot\text{yr}^{-1}$, which corresponds to the mean and median UV derived SFRs for Lyα emitters in the HETDEX pilot survey (Blanc et al. 2010). The resulting total intrinsic luminosity in Lyα photons is $L_{\text{Ly}\alpha} = 2.3 \times 10^{42}(1 - f_{\text{esc}})\text{erg s}^{-1}$. The escape fraction of ionizing photons, $f_{\text{esc}}$, is uncertain (e.g. Yajima, Choi & Nagamine 2010, and references therein) and may vary significantly between individual objects (Shapley et al. 2006). We consider two cases in the paper: $f_{\text{esc}} = 0.0$ and $f_{\text{esc}} = 0.1$. We calculate profiles at $z = 3.0$, for which $v_{\text{esc}} = 103$ km s$^{-1}$ and $r_{\text{esc}} = 39$ kpc. The background photoionization rate at $z = 3.0$ is taken to be $\Gamma_{bg} = 0.5 \times 10^{-12}$ s$^{-1}$ (Faucher-Giguère et al. 2008).

Examples of the intrinsic (grey lines) and transmitted (black lines) Lyα lines in this model are shown as a function of rest-frame wavelength in Fig. 5. We show cases in which no ionizing radiation escapes the galaxy (upper panels), and in which the escape fraction is $f_{\text{esc}} = 0.1$ (lower panels). The line profiles show the features of absorption redwards of the intrinsic Lyα central wavelength owing to the influence of gas infall, and no absorption redwards of the blue most edge. The three sets of panels show the dependence of the line profile on fluctuations in the density ($\rho$, left-hand panels), ionizing background ($\Gamma_{bg}$, central panels) and velocity gradient (d$v$/dr, right-hand panels). For each quantity, we present fluctuations (e.g. $\delta\rho \equiv pL\rho_0 - 1$, where $\rho_0$ is the fiducial model) of ±0.3 relative to the fiducial model. The resulting values of transmission $T$ are presented in Fig. 5. The transmission of the fiducial model is $T = 0.42$ for the case with $f_{\text{esc}} = 0$, and $T = 0.69$ for the case with $f_{\text{esc}} = 0.1$.

We incorporate these fluctuations into our model as follows. First, to vary the density $\rho$, we make the modifications (i) $n_{\text{HI}} \rightarrow n_{\text{HI}}(1 + \delta)$ and (ii) $T_{\text{gas}} \rightarrow T_{\text{gas}}(1 + [\gamma - 1]/\beta)$ in equation (3). This temperature change affects the recombination coefficient (see equation 6). Secondly, for variations in $\Gamma_{bg}$, we adjust $\Gamma_{bg}$ in equation (34). Finally, to study the impact of fluctuations in the velocity gradient, we multiply the optical depth in equation (1) by a factor of $(1 + b_v)$ in the linear regime beyond $10r_{\text{esc}}$, and by a factor of $(1 + b_{\text{manifest}})$ in the inflow region at $r < 10r_{\text{esc}}$. Though not self-consistent, this procedure preserves the density and velocity profiles, and so
isolates the effect of velocity gradient. To evaluate $\delta_{\text{infall}}$, we calculate fluctuations in velocity gradient within the infall region relative to the fiducial model with $\frac{\partial v}{\partial r} = 0$. Noting that $\frac{\partial v}{\partial r} = \frac{10v_\text{circ}}{r_\text{vir}}$, in the infall region, we keep the circular velocity and virial radius fixed, but replace $H$ with $H(1 + \delta_z)$ to modify the velocity gradient beyond the infall region. This results in a fluctuation in the velocity gradient within the infall region of

$$
\delta_{\text{infall}} = \frac{\frac{dv_{\text{infall}}}{dr} - \frac{dv_{\text{infall}}}{dr}|_0}{\frac{dv_{\text{infall}}}{dr}|_0} = \frac{\partial v}{\partial r} \approx \frac{1}{1 + 10Hr_\text{vir}/v_\text{vir}} \approx \delta_z/2,
$$

where in the last equality we have noted that the galaxy dynamical time is $v_\text{vir}/r_\text{vir} \sim 0.1 H^{-1}$. Thus fluctuations in velocity gradient within the infall region are reduced relative to those in the linear regime.

The line profiles in Fig. 5 illustrate that fluctuations in density and ionizing background lead to substantial modification of the transmitted flux profile on the blue side of the Lyα line, extending into the red side owing to infall. Fluctuations in density have a larger effect on the transmission than fluctuations in ionizing background, and the effects have opposite sign as discussed in Section 3.3. In the case where there is no contribution to the ionizing flux, the effects have opposite sign as discussed in our simple analytic model for $f_\text{esc} = 0$. The long-dashed grey curves show the transmission as a function of wavelength for the mean model. The upper row shows results assuming that the galaxy does not contribute to the ionizing flux. The lower row assumes an escape fraction of ionizing photons from the galaxy of $f_\text{esc} = 0.1$ per cent. The assumed halo mass was $10^{11} M_\odot$.

**Figure 5.** Example line profiles in the infall model, with modifications from adjustments in the density $\rho$ (left), the ionizing background $\Gamma$ (centre) and velocity gradient $d_\text{r}/dr$ (right). The vertical dashed line indicates the Lyα line centre. Values for the sizes of the fluctuations considered in these quantities are listed in each case, together with the resulting transmission. The long-dashed grey curves show the transmission as a function of wavelength for the mean model. The upper row shows results assuming that the galaxy does not contribute to the ionizing flux. The lower row assumes an escape fraction of ionizing photons from the galaxy of $f_\text{esc} = 0.1$ per cent. The assumed halo mass was $10^{11} M_\odot$.

The modelling of Section 4.1 assumes the intrinsic Lyα line emerging from the galaxy into the IGM to be a Doppler broadened Gaussian, which is symmetric in frequency around the Lyα resonance. However, galactic outflows have the effect of redshifting the emission of the ionizing background level has little effect on the transmission in regions where the galaxy dominates the ionizing flux. Based on these absorption profiles, we can estimate the quantities $\frac{\partial \ln T}{\partial \ln \rho}$, $\frac{\partial \ln T}{\partial \ln \Gamma}$ and $\frac{\partial \ln T}{\partial \ln (dv/dr)}$, and hence the values of the constants $C_\rho$, $C_\Gamma$ and $C_v$ which govern the modification of galaxy clustering. In the case where the galaxy makes no contribution to the ionizing flux ($f_\text{esc} = 0$), we find $C_\rho = -0.72$, $C_\Gamma = 0.32$ and $C_v = 0.20$. Inspection of Fig. 4 shows that these values are similar to those in our simple analytic model for $F \sim 0.65$ (corresponding to a fraction of the red half of the line having been absorbed due to infall), and $\tau \sim 2$ (which reproduces the infall model transmission at $\tau \sim 3$). In the case where $f_\text{esc} = 0.1$, the value of $C_\Gamma = 0.05$ is much smaller than for $f_\text{esc} = 0$, owing to the reduced relative importance of the ionizing background. Similarly, owing to the higher transmission, the $f_\text{esc} = 0.1$ model also leads to lower values of $C_\rho = -0.39$ and $C_v = 0.11$. We can again find approximate agreement when we compare these values of $C_\rho$ and $C_v$ to our simple analytic model (Fig. 4) assuming $F \sim 0.65$ and $\tau \sim 0.5$ (corresponding to the mean transmission of $T = 0.7$ for this model).

### 4.2 Modelling Lyα transmission in the presence of dust-free, symmetric ISM outflows

The modelling of Section 4.1 assumes the intrinsic Lyα line emerging from the galaxy into the IGM to be a Doppler broadened Gaussian, which is symmetric in frequency around the Lyα resonance. However, galactic outflows have the effect of redshifting the
emergent Lyα line relative to the true velocity of the galaxy (e.g. Ahn et al. 2003; Verhamme et al. 2006), and there is strong observational evidence that this mechanism is at work. This evidence includes the observed blueshift of interstellar metal absorption lines combined with the observed redshift of the Lyα emission line (Steidel et al. 2010), and the fact that Lyα line shapes are asymmetric at all redshifts (e.g. Mas-Hesse et al. 2003; Heckman et al. 2011). We refer the reader to Dijkstra, Mesinger & Wyithe (2011) for a more extended discussion. Verhamme et al. (2006, 2008) have developed a simple model in which scattering of Lyα photons by H1 in these outflows successfully explains the observed Lyα line shapes observed in Lyα emitting galaxies at z = 3–6 (also see Vanzella et al. 2010).

In this section we repeat the exercise of Section 4.1 for a suite of outflow models. Following Verhamme et al. (2006, 2008) and Dijkstra & Wyithe (2010), we model the outflow as a spherically symmetric thin shell of gas that contains an H1 column density $N_{\text{H1}}$ and outflow velocity $v_{\text{sh}}$. We assume that the shell has a radius of 1 kpc and a thickness of 0.1 kpc, but stress that the precise physical scale of the outflow is not important for our results. Our assumed gas temperature of $T_{\text{ISM}} = 10^4$ K in the outflowing H1 shell corresponds to a b-parameter of $\sim 13$ km s$^{-1}$ in the terminology of Verhamme et al. (2008). We further assume the H1 shells to be dust-free (see Section 4.3 for a discussion on dusty outflows). Verhamme et al. (2008) typically found that $\log N_{\text{H1}} \sim 19–21$ and $v_{\text{sh}} \sim 0–500$ km s$^{-1}$. We therefore assume a model in which $(N_{\text{H1}}, v_{\text{sh}}) = (10^{20} \, \text{cm}^{-2}, 200 \, \text{km s}^{-1})$. We compute Lyα spectra emerging from the outflows using a Monte Carlo transfer code (Dijkstra, Haiman & Spaans 2006). In our calculations, the Lyα photons are emitted at line centre ($\lambda_{\text{Ly} \alpha} = 1215.67$ Å). We compute the impact of the IGM on the directly observed fraction of Lyα by suppressing the intrinsic spectrum by $\exp(-\tau)$ (see Section 4.1). Further details on the calculation of this model can be found in Dijkstra et al. (2011). The grey solid line in Fig. 6 shows an example of the Lyα spectra emerging from the outflows. The emerging spectrum is highly asymmetric, with more flux coming out on the red side of the Lyα line centre. The spectrum peaks at about $\sim 2v_{\text{sh}}$, as expected for radiation that scatters back to the observer on the far side of the galaxy (see Ahn et al. 2003; Verhamme et al. 2006, for a detailed discussion on these features in the spectrum).

In Fig. 6 we show the transmitted (black lines) Lyα line for the outflow model. As in Fig. 5, we show cases in which no ionizing radiation escapes the galaxy (upper panels), and in which the escape fraction is $f_{\text{esc}} = 0.1$ (lower panels). As before, we show the dependence of the line profile on each of fluctuations in the density ($\rho$, left-hand panels), ionizing background ($\Gamma_{\text{bg}}$, central panels) and velocity gradient (d$v$/dr, right-hand panels). The resulting values of transmission $T$ are listed. The transmission of the fiducial outflow model is $T = 0.85$ where $f_{\text{esc}} = 0$, and $T = 0.94$ where $f_{\text{esc}} = 0.1$. These values are larger than were found for the infall case, owing to the large fraction of radiation that scatters away from resonance before emerging from the galaxy. All trends of the transmission with fluctuations in density, ionizing background and velocity gradient previously described for the infall model are also present in the outflow models. However, the modifications of the transmitted flux are smaller than are found in the infall case. This is because a smaller fraction of the emergent flux is subject to resonant absorption in the IGM.

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Based on these absorption profiles, we can estimate the values of the constants $C_\rho$, $C_T$ and $C_v$ which govern the modification of galaxy clustering in the outflow model. In the case where the galaxy makes no contribution to the ionizing flux, we find $C_\rho = -0.06$, $C_T = 0.04$ and $C_v = 0.02$. Inspection of Fig. 4 shows these values are similar to our simple analytic model with $F \sim 0.2$ (corresponding to most of the line having been scattered redwards of Ly$\alpha$ by the outflow) and $\tau \sim 2$ (which results in a transmission equal to that predicted by the detailed outflow model). In the case where $f_{\rm esc} = 0.1$, the value of $C_T = 0.005$ is much smaller than for the $f_{\rm esc} = 0$ case owing to the reduced importance of the ionizing background. Similarly, because of the higher transmission, the model with $f_{\rm esc} = 0.1$ also leads to lower values of $C_\rho = -0.05$ and $C_v = 0.01$. We again find approximate agreement when we compare these values for $C_\rho$ and $C_v$ to our simple analytic model (Fig. 4) with $F \sim 0.2$ and $\tau \sim 0.5$, corresponding to the mean transmission of $T = 0.94$ for this model.

4.3 Modelling the IGM transmission for dusty, anisotropic outflows

The calculations presented in Section 4.2 ignore the impact of dust on the Ly$\alpha$ radiation field. However dust can play an important role in the scattering of Ly$\alpha$ photons within galaxies (e.g. Neufeld 1991; Hansen & Oh 2006). Laursen, Sommer-Larsen & Andersen (2009) have performed Ly$\alpha$ radiative transfer calculations in simulated galaxies, finding that the effect of dust is to narrow the Ly$\alpha$ line emerging from a galaxy relative to the dust-free case. Narrowing the Ly$\alpha$ line causes a larger fraction of Ly$\alpha$ photons to emerge at frequencies where they are subject to scattering in the IGM. We therefore expect the impact of the IGM to be stronger in cases where dust is included in the modelling of outflows.

In our model, the galactic outflow is represented by a spherical shell. Departures from this idealized gas distribution should also lead to a larger impact of the IGM on the emerging Ly$\alpha$ line. This is because Ly$\alpha$ photons will escape more easily from outflows in which either the covering factor is less than unity (because some sightlines simply do not intersect with the outflowing material) or when the scattering medium is clumpy. The latter is demonstrated by Hansen & Oh (2006) who have studied Ly$\alpha$ transfer through clumpy outflows, and have shown that a fraction of the photons can escape at line centre. These results suggest that more complicated and realistic models of winds than those employed in this paper will result in a stronger impact of the IGM on the observed Ly$\alpha$ flux than we have computed here (Section 4.2, also see Barnes et al. 2011).

4.4 Summary of detailed modelling

The values of $C_\rho$, $C_T$ and $C_v$ found from the detailed modelling in this section are summarized in Table 1. The prediction from the infall model for Ly$\alpha$ transmission is that there will be significant contributions to the observed power spectrum from fluctuations in the Ly$\alpha$ transmission. Indeed, if the escape fraction of ionizing photons is very small, then the contributions are expected to be of order unity. In contrast, the prediction from the outflow model is that contributions to the observed power spectrum will be an order of magnitude smaller, at the level of $\sim 5$–10 per cent, although these numbers are likely to be conservatively small (see Section 4.3).

These results suggest that measurement of the terms $C_\rho$, $C_T$ and $C_v$ from the observed power spectrum of Ly$\alpha$ selected galaxies will provide a new avenue to study the relationship between the Ly$\alpha$ flux of galaxies and their local IGM. On the other hand, the expected non-zero values of $C_\rho$, $C_T$ and $C_v$ may complicate attempts to use the power spectrum of Ly$\alpha$ selected galaxies to constrain cosmological parameters. We turn to this topic for the remainder of the paper, in which we present an application of our general model for clustering of Ly$\alpha$ selected galaxies to the planned HETDEX survey.

| Model       | $C_\rho$ | $C_T$ | $C_v$ |
|-------------|---------|-------|-------|
| Infall ($f_{\rm esc} = 0$) | -0.72   | 0.32  | 0.20  |
| Infall ($f_{\rm esc} = 0.1$) | -0.39   | 0.05  | 0.11  |
| Outflow ($f_{\rm esc} = 0$) | -0.06   | 0.04  | 0.02  |
| Outflow ($f_{\rm esc} = 0.1$) | -0.05   | 0.005 | 0.01  |

5. LY$\alpha$ transmission fluctuations in galaxy redshift surveys

One of the primary science drivers motivating large galaxy redshift surveys is measurement of dark energy and its evolution. Traditional galaxy redshift surveys are best suited to studies of the dark energy equation of state at relatively late times ($z < 1$) due to the difficulty of obtaining accurate redshifts for a sufficiently large number of high-redshift galaxies. Although detection of the integrated Sachs–Wolfe effect puts some constraints on the integrated role of dark energy above $z \gtrsim 1.5$ (see e.g. Giannantonio et al. 2008, and references therein), we currently have very limited information about the nature of dark energy at high redshift. If dark energy behaves like a cosmological constant, then its effect on the Hubble expansion is only significant at $z \lesssim 1$ and becomes small at $z \gtrsim 2$. In this case, studies of the power spectrum at low redshift would provide the strongest constraints. However, as the origin of dark energy is not understood we cannot presume a priori which redshift range should be studied in order to provide optimal constraints on proposed models. Probes of dark energy at higher redshifts have been suggested. These include measurements of the power spectrum from a Ly$\alpha$ forest survey, which could potentially be used to probe the evolution of dark energy through measurement of the baryonic acoustic oscillation (BAO) scale for redshifts as high as $z \sim 4$ (McDonald & Eisenstein 2007). Similarly, studying the temporal variation of high-resolution quasar spectra may probe the evolution of dark energy in the window $2 < z < 5$ (Corasaniti, Hutner & Melchiorri 2007).

The HETDEX (Hill et al. 2004, 2008) promises to provide a very important advance in our understanding of dark energy, by measuring its contribution to the energy density at high redshift ($z \sim 2.5$) where there are currently no direct constraints. At the same time, a precision measurement of curvature will assist in breaking the degeneracy between dark energy and curvature present in lower redshift experiments (Hill et al. 2004; McDonald & Eisenstein 2007). The HETDEX approach is to obtain approximately 0.8 million redshifts of Ly$\alpha$ selected galaxies at $1.9 < z < 3.5$. These galaxies will be obtained over an area of 400 deg$^2$, with a survey volume of $V \sim 9$ Gpc$^3$, and a galaxy space density of $n_{\text{Ly} \alpha} \sim 10^{-4}$ Mpc$^{-3}$. In the

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Table 1. Evaluations of the constants $C_\rho$, $C_T$ and $C_v$ for the different models.

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6 This is mostly because Ly$\alpha$ scattering can be described by a diffusion process in both real and frequency space (see Dijkstra et al. 2006, and references therein). A large displacement in frequency requires a large number of scatterings, and therefore a long trajectory through the scattering medium. As the dust content of this medium is increased, the probability that the photon is destroyed by a dust grain is enhanced.
absence of non-gravitational contributions to the clustering, such a survey is able to use the measured power spectrum to determine the local Hubble expansion at $z \sim 2.5$, and the angular diameter distance out to $z \sim 2.5$ at a level of 0.8 per cent each. In this section we discuss the influence that the non-gravitational contribution to the observed power spectrum of Ly$\alpha$ selected galaxies may have on the precision of cosmological constraints from a survey like HETDEX.

We find that the transmission can strongly influence the constraints that are available, and determine the precision with which the parameters $C_{\tau}$, $C_\gamma$ and $C_\rho$ will need to be understood in order for HETDEX to achieve its theoretical precision.

### 5.1 Power spectrum and power-spectrum sensitivity

In this section we describe the power spectrum, and the estimate of power-spectrum sensitivity, that we employ to calculate the influence of transmission fluctuations on cosmological constraints that will be available in HETDEX. Analysis of the galaxy power spectrum derived from $N$-body simulations has shown (See & Eisenstein 2005) that the power spectrum can be treated as linear on scales greater than 15 comoving Mpc (i.e. $k_{\text{max}} \lesssim 0.4$ Mpc$^{-1}$) at $z = 3.5$, increasing towards higher redshifts. Our assumption of a linear mass power spectrum should therefore be sufficient for this analysis. However, weak oscillatory features in the power spectrum, such as the BAOs, are suppressed on even larger scales because matter moves across distances on the order of $\sim 5$–10 Mpc over a Hubble time.

As groups of galaxies form, the linear-theory prediction for the location of each galaxy becomes uncertain, and as a result noise is added to the correlation among galaxies and hence to the measurement of the mass power spectrum. The noise associated with the movement of galaxies smears out the acoustic peak in the correlation function of galaxies in both real and redshift space (Eisenstein et al. 2007; See et al. 2008). The associated reduction of power in the BAOs is found to be in excess of 70 per cent on scales smaller than $k_{\text{max}} \sim 0.4$ Mpc$^{-1}$ at $z \sim 3$, corresponding to a length-scale of $\sim \pi/(2k_{\text{max}}) = 3.9$ comoving Mpc (See et al. 2008), though we note that it is difficult to be precise about the range of scales where the matter power spectrum at high redshift can be considered linear because the scale of departure from linearity depends on the accuracy requirements (See et al. 2010). Moreover, Ly$\alpha$ galaxies will be significantly biased (we have chosen a bias of 2.25), and non-linear effects will be found at the scale where the galaxy fluctuations (not mass fluctuations) are order unity. Based on these considerations, we use the following mass power spectrum for our cosmological analysis:

$$P_{m,\text{m}}(k) = P_{m,\text{nw}}(k) + \left[ P_m(k) - P_{m,\text{nw}}(k) \right] \exp \left[ -k^2 \frac{\Sigma_\perp(1 - \mu^2) + \Sigma_\parallel \mu^2}{2} \right],$$

where $P_{m,\text{nw}}$ is the ‘no wiggle’ form from Eisenstein & Hu (1999). The non-linear scales in this expression are $\Sigma_\perp = 4.6(1 + z/3.5)^{-1}$ Mpc and $\Sigma_\parallel = 9.2(1 + z)/3.5$ Mpc (See & Eisenstein 2007) in the high-redshift limit. Note that we consider only scales $k < 0.4$ Mpc$^{-1}$, and so do not include the effects of the fingers-of-god that arise from random motions within virialized haloes in our analysis. As shown in Shoji, Jeong & Komatsu (2009), this has no influence on the cosmological constraints inferred from the large-scale power spectrum.

Like traditional galaxy redshift surveys, the observed Ly$\alpha$ galaxy power spectrum is sensitive to the underlying mass power spectrum ($P_m$) and galaxy bias $b$. However, in addition, there is also dependence on the parameters $C_{\tau}$, $C_\gamma$, $C_\rho$, which are related to properties of Ly$\alpha$ transmission through the IGM, and on the mean free path $\lambda$. Inspection of equations (17) and (19) indicates that not all of $b$, $C_\rho$ and $C_\tau$ can be measured independently. Instead, the power spectrum of Ly$\alpha$ emitting galaxies depends on the parameters $bc_{\tau}$, $(C_\rho + b)$ and $C_\gamma$. In the left-hand panel of Fig. 7 we plot the predicted spherically averaged power spectrum of Ly$\alpha$ galaxies, using equation (19) with the combinations $[C_{\tau}, bc_{\tau}, (b + C_\rho)] = (0, 0, 2.5)$ and $(0.5, 0.1, 2.5)$. These parameters are motivated by an extreme outflow model (Section 4.2) and an infall model (Section 4.1), respectively.

Fig. 7 also presents error bars assuming the observational survey parameters $V \sim 9$ Gpc$^3$ and $n_L \sim 10^{-4}$ Mpc$^{-3}$ appropriate for HETDEX. We evaluate the uncertainty in a k-space volume $2\pi k^2\Delta k \sin(\mu) \Delta \mu$ as

$$\Delta P_{\text{ly}} = P_{\text{ly}} \left( 1 + \frac{1}{P_{\text{ly}} \mu_{\text{ly}}} \right) \left( k^2 \Delta k \sin(\mu) \Delta \mu \frac{V}{(2\pi)^2} \right)^{-1/2},$$

where the sum in the first term encapsulates cosmic variance and galaxy shot noise respectively, and the second term corresponds to the number of modes measured in the survey. We find that shot noise dominates at $k \gtrsim 0.1$ Mpc$^{-1}$. The right-hand panel of Fig. 7 shows the BAOs, plotted as fluctuations relative to the ‘no wiggle’ power spectrum.

### 5.2 Measurement of BAOs with Ly$\alpha$ selected galaxies

The imprint of BAOs on the mass power spectrum provides a cosmic yardstick that can be used to measure the dependence of both the angular diameter distance and Hubble parameter on redshift. The wavelength of a BAO is related to the size of the sound horizon at recombination. Its value depends on the Hubble constant, and on the dark matter and baryon densities. However, it does not depend on the amount or nature of dark energy. Thus, measurements of the angular diameter distance and Hubble parameter can in turn be used to constrain the possible evolution of dark energy with cosmic time (e.g. Eisenstein, Hu & Tegmark 1998; Eisenstein 2002).

Importantly, a measurement of the BAO scale is not subject to modifications of the overall shape or angular dependence of the power spectrum, owing to non-linear gravitational growth. To illustrate this point, See & Eisenstein (2005) modelled the power spectra from a series of $N$-body simulations using the addition of a linear power spectrum and a scale-dependent polynomial to describe galaxy bias and anomalous power. See & Eisenstein (2005) find that they are able to recover the BAO signal by subtracting a smooth function from the matter power spectrum measured in their $N$-body simulations.

Our model is intrinsically linear and so does not include scale-dependent bias or anomalous power. However, the subtraction of a smooth function to recover the BAO signal is valid for a range of different scale-dependent contributions (e.g. Mao et al. 2008; Rhook, Geil & Wyithe 2009). As a result, while Ly$\alpha$ transmission fluctuations inhibit the extraction of the full cosmological information through consideration of the whole power spectrum, they should not significantly alter the ability of a Ly$\alpha$ galaxy survey to measure the BAO scale.

To illustrate this point, we have fitted the analytic approximation to the baryonic oscillation component of the redshift space power
The clustering of Lyα emitters

Figure 7. Left-hand panel: the predicted spherically averaged power spectrum of Lyα galaxies, using equation (19) with the combinations \([C_v, bC_T, (b+C_p)] = (0, 0, 2.5)\) and \((0.5, 0.1, 2.5)\). Right-hand panel: the BAOs, plotted as fluctuations relative to the ‘no wiggle’ power spectrum. The error bars assuming the observational survey parameters \(V \sim 9\, \text{Gpc}^3\) and \(n_{\text{gal}} \sim 10^{-4}\, \text{Mpc}^{-3}\) that are appropriate for HETDEX, with each point providing an independent measures of the power.

spectrum following Glazebrook & Blake (2005):

\[
P_{13}(k_1, k_\perp) = P_{13,\text{nw}}(k_1, k_\perp) \times \left\{ 1 + Ak \exp \left[ -\left( \frac{k}{0.07\, \text{Mpc}^{-1}} \right)^{1.4} \right] \right\},
\]

\[
\times \sin \left( 2\pi \frac{k_\perp}{(1 + \alpha_\perp k_\perp)} + \frac{k_\parallel}{(1 + \alpha_\parallel k_\parallel)} \right),
\]

\[
\times \exp \left( -k^2 \frac{\Sigma_1^2(1 - \mu^2) + \Sigma_2^2\mu^2}{2} \right),
\]

(40)

to estimate the constraints on the line of sight and transverse BAO scales \((\alpha_\parallel\) and \(\alpha_\perp\)). In this expression, the ‘wiggle free’ power spectrum \(P_{13,\text{nw}}\) is computed using equation (17), with the mass power spectrum \(P_m\) replaced by the ‘wiggle free’ mass-power spectrum \(P_{m,\text{nw}}\). The observed power spectrum \(P_{13}\) is modelled as the sum of \(P_{13,\text{nw}}\) and a decaying sinusoid with characteristic periods in the line of sight and transverse directions of \((1 + \alpha_\parallel k_\parallel)\) and \((1 + \alpha_\perp k_\perp)\). We include the factor of non-linear suppression of the BAO amplitude (Seo & Eisenstein 2007). This function has three parameters: \(A\), \(\alpha_\parallel\), and \(\alpha_\perp\). The value of \(A\) is determined to high accuracy from observations of the cosmic microwave background. For the purposes of this analysis, we therefore assume that \(A\) is a known constant (namely \(A = 2.1\)) and fit only for \(\alpha_\parallel\) and \(\alpha_\perp\) (around the best-fitting value of \(k_\parallel\) in the absence of noise). We fit only to values of \(k < 0.4\, \text{Mpc}^{-1}\). With this parametrization, the accuracy with which \(\alpha_\parallel\) and \(\alpha_\perp\) can be measured determines the constraints that BAO can place on the line of sight and transverse distances, and hence on the Hubble parameter \(H\) and angular diameter distance \(D_A\), respectively.

In Fig. 8 we show contours of \(\alpha_\parallel\) and \(\alpha_\perp\) derived from the BAO analysis. For graphical representation of our results, we show contours at 61 and 14 per cent of the peak height. The values of 61 per cent \(\sim e^{-\Delta \chi^2/2}\) and 14 per cent \(\sim e^{-\Delta \chi^2/4}\) are chosen to equal the contour height corresponding to \(\Delta \chi^2 = 1\) and \(\Delta \chi^2 = 4\), and therefore the projection of these contours on to the axis for a particular parameter represents the 1σ and 2σ ranges, respectively. The left-hand panel shows the expectations for a galaxy redshift survey with parameters corresponding to HETDEX. Our analysis yields 1σ errors of \(\Delta \alpha_\parallel \sim 3.0\) per cent and \(\Delta \alpha_\perp \sim 2.0\) per cent. For consistency, we compare with the BAO constraints for HETDEX presented in Shoji et al. (2009). These authors find similar constraints of \(\Delta \alpha_\parallel \sim 2.5\) per cent and \(\Delta \alpha_\perp \sim 1.8\) per cent.

In the central and right-hand panels of Fig. 8, we allow for scale- and direction-dependent modifications to the power spectrum owing to fluctuations in Lyα transmission (equation 17). In these cases, the fiducial models have \((C_v, bC_T) = (0, 0)\) and \((C_v, bC_T) = (0.5, 0.1)\), respectively. No prior probabilities on their values were assumed. There is a very small difference in the resulting BAO constraints, indicating that modification of the power spectrum by fluctuations in Lyα transmission will not inhibit use of the BAO scale for studies of dark energy in Lyα selected galaxy surveys. The values for constraints on \(\alpha_\parallel\) and \(\alpha_\perp\) are listed in Table 2.

5.3 Application of the Alcock–Paczynski test

Shoji et al. (2009) have argued that much more accurate constraints on cosmological distances are obtained by consideration of the whole power spectrum shape rather than only the BAO scale. To quantify the potential of the Lyα galaxy power spectrum for measuring cosmological parameters, we therefore calculate the Alcock–Paczynski effect (Alcock & Paczynski 1979). Our approach is to specify the general result of Barkana (2006) for the distortion of the true power spectrum \([P_{13}(k, \mu)]\) that results from an incorrect choice of cosmology. Dilation parameters \(\alpha_\parallel\) and \(\alpha_\perp\) are used to describe the distortions between the transverse and line-of-sight scales, and in the overall scale, respectively. These are defined such that \(1 + \alpha\) is the ratio between the assumed and true values of \((D_A H)\), while \((1 + \alpha_\parallel)\) is the ratio between the assumed and true values of the angular diameter distance, \(D_A\). In the Alcock–Paczynski test, the correct cosmology is inferred by finding cosmological parameters for which \(\alpha = \alpha_\parallel = 0\).

To calculate the Alcock–Paczynski effect, we apply equation (8) in Barkana (2006):

\[
P_{13}(k, \mu) = (1 + \alpha) P_{13}^{\mu} + (\alpha \mu^2 - \alpha_\parallel) \frac{\partial P_{13}^{\mu}}{\partial \ln k} \frac{\partial P_{13}^{\mu}}{\partial \ln \mu} + \alpha(1 - \mu^2) \frac{\partial P_{13}^{\mu}}{\partial \ln k} \frac{\partial P_{13}^{\mu}}{\partial \ln \mu}.
\]

(41)
The light and parallel BAO scale. The three panels show contours of likelihood for the parameter set $\alpha_{\perp}, \alpha_{\parallel}$, in the cases of a traditional galaxy power spectrum (left), and Ly$\alpha$ galaxy power spectra with $[C_v, bC_T, (b+C_\sigma)] = (0, 2.5)$ (central) and $[C_v, bC_T, (b+C_\sigma)] = (0.5, 0.1, 2.5)$ (right), respectively. Contours of likelihood for the values of $\alpha_{\parallel}$ and $\alpha_{\perp}$ are shown (at 61 and 14 per cent of the peak likelihood). The values of 61 per cent $\sim e^{-\Delta \chi^2/2}$ and 14 per cent $\sim e^{-\Delta \chi^2/2}$ are chosen to equal the contour height corresponding to $\Delta \chi^2 = 1$ and $\Delta \chi^2 = 4$, and therefore the projection of these contours on to the axis for a particular parameter represents the 1-$\sigma$ and 2-$\sigma$ ranges, respectively. The 61 per cent contour for the traditional galaxy redshift survey constraints is repeated in the central and right-hand panels for comparison (thick dotted line).

Table 2. Summary of constraints on $\alpha_{\parallel}$ and $\alpha_{\perp}$ for the different survey’s and analysis methods. The label ‘galaxy’ refers to an analysis that includes marginalization over $bC_T$ and $C_v$. The labels ‘BAO’ and ‘AP’ refer to constraints based on the BAO scale using equation (40) and the power-spectrum shape via equation (42), respectively. Where relevant, the values of the fiducial model $C_v$ and $bC_T$, and the corresponding prior constraints $\sigma_v$ and $\sigma_{bC_T}$ are listed.

| Survey | Constraint | $C_v$ | $bC_T$ | $\sigma_v$ | $\sigma_{bC_T}$ | $\Delta \alpha_{\parallel}$ (per cent) | $\Delta \alpha_{\perp}$ (per cent) |
|--------|------------|-------|-------|-----------|-------------|------------------|------------------|
| Galaxy | BAO        | –     | –     | –         | –           | 2.0               | 3.0               |
| Ly$\alpha$ gal. | BAO | 0     | 0     | –         | –           | 2.0               | 3.0               |
| Ly$\alpha$ gal. | BAO | 0.5   | 0.1   | –         | –           | 2.10              | 3.25              |
| Galaxy | AP         | –     | –     | –         | –           | 0.70              | 0.85              |
| Ly$\alpha$ gal. | AP | 0     | 0     | –         | –           | 1.25              | 1.35              |
| Ly$\alpha$ gal. | AP | 0.5   | 0.1   | –         | –           | 1.35              | 1.80              |
| Ly$\alpha$ gal. | AP | 0     | 0     | 1.0       | 1.0         | 1.20              | 1.35              |
| Ly$\alpha$ gal. | AP | 0     | 0     | 0.05      | 0.25        | 1.05              | 1.10              |
| Ly$\alpha$ gal. | AP | 0     | 0     | 0.02      | 0.1         | 0.80              | 1.00              |
| Ly$\alpha$ gal. | AP | 0     | 0     | 0.01      | 0.05        | 0.75              | 0.90              |

For dark energy studies, it is more interesting to constrain the quantities $D_H$ and $H$ independently rather than $D_H$ and the product $D_H H$. We define the dilation parameter $\alpha_{\parallel}$ such that $(1 + \alpha_{\parallel})$ is the ratio between the assumed values of $H$. The dilation parameter $\alpha$ in equation (42) is then expressed as

$$\alpha = 1 + \alpha_{\parallel} - 1.$$

Equation (42) can then be used to find the precision of constraints on $H$ and $D_H$. Inspection of equation (42) suggests that some degeneracies are expected between cosmological constraints (parametrized by $\alpha_{\parallel}$ and $\alpha_{\perp}$) and the unknown parameters describing the modification to the power spectrum owing to Ly$\alpha$ transmission fluctuations.

### 5.4 Alcock–Paczynski constraints on the power spectrum

We next use equation (42) to calculate the permissible region of parameter space $p = (\alpha_{\parallel}, \alpha_{\perp}, b + C_\sigma, C_v, bC_T)$ around a true solution with power spectrum $P_{L_5}^0$ and $P_{L_5} = (0, 0, 2.5, 0, 0)$. We have assumed that the mean free path of ionizing photons is known a priori, and do not fit it as a free parameter. We take the value to be $\lambda_{amp} = 300$ comoving Mpc (Bolton & Haehnelt 2007; Faucher-Giguère et al. 2008). Using the power-spectrum sensitivity specified in equation (39), we construct likelihoods

$$\ln L(p) = - \frac{1}{2} \sum_{k, \mu} \left[ \frac{P_{L_5}(k, \mu, p) - P_{L_5}^0(k, \mu, p_0)}{\Delta P_{L_5}(k, \mu)} \right]^2 + \ln L_{C_v} + \ln L_{C_T} + \ln L_{C_H},$$

where $L_{C_v}$, $L_{C_T}$, and $L_{C_H}$ are the likelihoods for the parameters $C_v$, $C_T$, and $C_H$, respectively.
where the sum is over bins of $k$ and $\mu$, and $\mathcal{L}_{C_\perp}$, $\mathcal{L}_{C_\parallel}$, and $\mathcal{L}_{bC}$ are the a priori likelihoods for the parameters $b + C_\rho$, $C_\rho$ and $bC_r$, respectively. To account for the possibility of non-linearity in the smooth power spectrum at small scales, we restrict our fitting to wavenumbers $k_{\text{max}} < 0.4 \, \text{Mpc}^{-1}$.

### 5.5 Constraints for a traditional galaxy redshift survey

To provide a baseline for our analysis, we first consider the case where Ly$\alpha$ transmission has no effect on observed galaxy flux (i.e. we consider only power spectra with $C_\rho = C_r = 0$), as is the case for a traditional galaxy redshift survey. For this analysis, we further assume that the value of $f$ is known and that the shape of the primordial power spectrum is well measured by other means. We refer to these constraints as being for a traditional galaxy redshift survey in the remainder of this paper. As discussed in Section 5.8, Shoji et al. (2009) have investigated the consequences of relaxing these strict prior constraints.

As noted in Section 5.3, the parameters $\alpha_\perp$ and $\alpha_\parallel$ are defined such that $(1 + \alpha_\perp)$ is the ratio between the assumed and true values of $(H_z)$, while $(1 + \alpha_\parallel)$ is the ratio between the assumed and true values of the angular diameter distance, $D_A$. Thus, the precision with which $\alpha_\perp$ can be measured provides an estimate of the relative precision with which $D_A$ can be measured. Similarly, precision with which the local value of $H$ can be measured is provided by the precision with which $\alpha_\parallel$ can be measured.

The left-hand panel of Fig. 9 presents likelihood contours for the parameter set $(\alpha_\perp, \alpha_\parallel)$ obtained from a traditional galaxy redshift survey assuming the HETDEX volume and galaxy density. The likelihood is marginalized over the bias $b$ assuming a flat prior probability. The contours show a degeneracy between $\alpha_\perp$ and $\alpha_\parallel$. This negative correlation is fundamental to the Alcock–Paczynski effect. When the redshift space distortion is known perfectly well, the departure of the real-space power spectrum from isotropy can be used to determine $D_A H$ (or $\alpha$ in equation (41)). Fig. 9 indicates that line-of-sight and angular distortions of the power spectrum compared with an assumed model can be measured at better than the ~1 per cent level, indicating that our analysis is consistent with expectations for the HETDEX survey. Comparison with Fig. 8 shows that the precision available on the line of sight and radial distances measured from the Alcock–Paczynski test using the full power-spectrum shape are a factor of several better than from an analysis of the BAO scale alone (Shoji et al. 2009). Values for these and subsequent constraints on $\alpha_\parallel$ and $\alpha_\perp$ are listed in Table 2.

### 5.6 Constraints for a Ly$\alpha$ galaxy redshift survey

We next calculate the level to which Ly$\alpha$ transmission fluctuations influence the precision with which $\alpha_\parallel$ and $\alpha_\perp$ can be measured. The central panel of Fig. 9 presents likelihood contours for the parameter set $(\alpha_\perp, \alpha_\parallel)$ obtained from a Ly$\alpha$ galaxy survey, again assuming the HETDEX volume and galaxy density, with a fiducial model having $[C_\rho, bC_r, (b + C_\rho)] = (0, 0, 2.5)$. Here the likelihood is marginalized over the parameters $C_\rho, bC_r$ and $(b + C_\rho)$ assuming flat prior probabilities (i.e. $\mathcal{L}_{C_\rho} = \mathcal{L}_{C_r} = \mathcal{L}_{bC} = \text{const}$). The $1\sigma$ contour for the traditional galaxy redshift survey case is repeated for comparison. Fig. 9 indicates that without knowledge of detailed properties of Ly$\alpha$ transmission (enabling prediction of $C_\rho$, $C_r$ and $bC_r$), the line-of-sight and angular distortions of the power spectrum can be measured at the ~1.3 per cent level, a factor of ~1.5 decrease in the available cosmological precision relative to a traditional galaxy redshift survey.

To calculate the constraints on $\alpha_\parallel$ and $\alpha_\perp$ for a Ly$\alpha$ galaxy survey, we must specify the transmission model. In the above calculation, we assumed a fiducial model with no transmission effects, but allowed for their possible existence when performing the cosmological fit. In the right-hand panel of Fig. 9, we repeat this analysis for an assumed fiducial model which has $[C_\rho, bC_r, (b + C_\rho)] = (0.5, 0.1, 2.5)$, and so includes strong modification of the observed power spectrum from fluctuations in Ly$\alpha$ transmission. In this case, we find that constraints on the angular distortions of the power spectrum are unchanged (~1.3 per cent), but that the line-of-sight distortions can only be measured at the ~1.7 per cent level.

To investigate the origin of the decrease in precision that follows inclusion of Ly$\alpha$ transmission fluctuations in a power-spectrum analysis, we show contours of likelihood for the parameter sets $(C_\rho, \alpha_\parallel)$, $(\alpha_\perp, C_\parallel)$, $(\alpha_\perp, bC_r)$ and $(bC_r, \alpha_\parallel)$ in the cases of $[C_\rho, bC_r, (b + C_\rho)] = (0.5, 0.1, 2.5)$ (central) and $[C_\rho, bC_r, (b + C_\rho)] = (0, 0, 2.5)$ (Figs 10 and 11, respectively). For each set, the likelihood is marginalized over the remaining parameters assuming flat prior probabilities. The figures show strong degeneracies as apparent from equation (42).

---

**Figure 9.** Constraints on power-spectrum distortions achievable via the Alcock–Paczynski test. The three panels show contours of likelihood for the parameter set $(\alpha_\perp, \alpha_\parallel)$ in the cases of a traditional galaxy power spectrum (left), and Ly$\alpha$ galaxy power spectra with $[C_\rho, bC_r, (b + C_\rho)] = (0, 0, 2.5)$ (central) and $[C_\rho, bC_r, (b + C_\rho)] = (0.5, 0.1, 2.5)$ (right), respectively. Contours of likelihood for the values of $\alpha_\perp$ and $\alpha_\parallel$ are shown (at 61 and 14 per cent of the peak likelihood). The 61 per cent contour for the traditional galaxy redshift survey constraints is repeated in the central and right-hand panels for comparison (thick dotted line).
Figure 10. Constraints on power-spectrum distortions and transmission models achievable via the Alcock–Paczynski test. The six panels show contours of likelihood for the parameter sets \((C_v, \alpha_\parallel), (\alpha_\perp, C_v), (\alpha_\perp, bC_\Gamma), (bC_\Gamma, \alpha_\parallel), (C_v, b + C_\rho)\) and \((bC_\Gamma, b + C_\rho)\), in the case of a Ly\(\alpha\) galaxy power spectrum with \([C_v, bC_\Gamma, (b + C_\rho)] = (0, 0, 2.5)\). Contours of likelihood for the values of \(\alpha_\parallel\) and \(\alpha_\perp\) are shown (at 61 and 14 per cent of the peak likelihood).

Figure 11. Constraints on power-spectrum distortions and transmission models achievable via the Alcock–Paczynski test. As per Fig. 10, but for the case of a Ly\(\alpha\) galaxy power spectrum with \([C_v, bC_\Gamma, (b + C_\rho)] = (0.5, 0.1, 2.5)\).
These degeneracies represent the origin of the weakened constraints on \( \alpha_\parallel \) and \( \alpha_\perp \), which arise because the transmission fluctuations introduce scale and angular dependencies into the power spectrum that mimic those introduced by an incorrect choice of cosmology. In particular, Fig. 9 shows that the correlation between \( \alpha_\parallel \) and \( \alpha_\perp \) nearly disappears. This is because by marginalizing over \( C_v \), the redshift space distortions are now not perfectly known (as was assumed for the traditional galaxy redshift survey case), so that the Alcock–Paczynski test cannot be used to measure \( D_\parallel H \).

We have also computed the contours of likelihood for the parameter sets \((C_v, b + C_v)\) and \((bC_v, b + C_v)\) in the cases of \([C_v, bC_v, (b + C_v)] = (0.5, 0.1, 2.5)\) and \([C_v, bC_v, (b + C_v)] = (0, 0, 2.5)\) (Figs 10 and 11, respectively). These can be considered in addition to the constraints \((C_v, \alpha_\parallel), (\alpha_\parallel, C_v), (\alpha_\perp, bC_v), (bC_v, \alpha_\parallel)\), and represent estimates for the available constraints on transmission models. For each set, the likelihood is marginalized over the remaining parameters assuming flat prior probabilities. The parameters \( C_v \) and \( bC_v \) describing the transmission model show very little degeneracy with each other. However, constraints on \( C_v \) are degenerate with the power-spectrum amplitude \((b + C_v)\). The constraints of these parameters are similar in magnitude for the two fiducial models considered. Without detailed prior knowledge of the cosmology (i.e. no prior on \( \alpha_\parallel \) or \( \alpha_\perp \)), a Ly\( \alpha \) survey like HETDEX could determine uncertainties in \( C_v, bC_v \) and \((b + C_v)\) of \( \Delta C_v \sim \pm 0.04, \Delta bC_v \sim \pm 0.2 \) and \( \Delta (b + C_v) \sim \pm 0.02 \). We discuss constraints on transmission models in more detail in Section 6.

5.7 Cosmological constraints including prior probabilities for \( C_v \) and \( bC_v \)

We have shown that fluctuations in Ly\( \alpha \) transmission decrease the precision with which the angular diameter distance and Hubble parameter can be measured at \( z \sim 2.5 \), relative to measurements from a traditional galaxy redshift survey. Assuming no prior knowledge of \( C_v \) and \( bC_v \), the decrease is found to be a factor of \( 1.5-2 \). On the other hand, if the parameters describing the Ly\( \alpha \) transmission fluctuations are separately constrained, then the degeneracies seen in Figs 10 and 11 imply that the parameters \( \alpha_\parallel \) and \( \alpha_\perp \) will be measured with increased precision. In this section we investigate the degree of prior knowledge regarding transmission of Ly\( \alpha \) flux (as parametrized by \( C_v \) and \( bC_v \)) that is required in order to achieve measurements of cosmological parameters with a precision that would be available in a traditional galaxy redshift survey.

Fig. 12 shows the constraints on power-spectrum distortions that are achievable via the Alcock–Paczynski test in cases where there are prior constraints on \( C_v \) and \( bC_v \). Each panel shows contours of likelihood for the parameter set \((\alpha_\parallel, \alpha_\perp)\), in the case of a Ly\( \alpha \) galaxy power spectrum with \([C_v, bC_v, (b + C_v)] = (0, 0, 2.5)\). To compute these constraints, we have assumed prior likelihoods of

\[
\mathcal{L}_{C_v}(C_v) = \exp \left[ -\frac{(C_v - \langle C_v \rangle)^2}{2\sigma_{C_v}^2} \right]
\]

and

\[
\mathcal{L}_{bC_v}(bC_v) = \exp \left[ -\frac{(bC_v - \langle bC_v \rangle)^2}{2\sigma_{bC_v}^2} \right],
\]

where \([C_v] \) and \([bC_v] \) are the means of \( C_v \) and \( bC_v \) corresponding to the fiducial model, and \( \sigma_{C_v} \) and \( \sigma_{bC_v} \) are the prior uncertainties in \( C_v \) and \( bC_v \), respectively. Fig. 12 is presented as a grid, with prior precision on \( C_v \) increasing from left to right, and prior precision on \( bC_v \) increasing from top to bottom. The four columns show constraints assuming \( \sigma_\parallel = 1 \), \( 0.05, 0.02 \) and 0.01. For each of these columns, four rows are shown with \( \sigma_{bC_v} = 1, 0.25, 0.1 \) and 0.05. The 61 per cent contour for the traditional galaxy redshift survey constraints is repeated in all panels for comparison (thick dotted lines).

As the prior precision on \( bC_v \) is increased, the precision with which \( \alpha_\parallel \) is measured increases. As the prior precision on \( C_v \) is increased, the strength of the correlation between \( \alpha_\parallel \) and \( \alpha_\perp \) is increased. This signifies that the parameter \( C_v \) is degenerate with the Alcock–Paczynski effect. As a result, precision in \( \alpha_\parallel \) requires prior knowledge of both \( bC_v \) and \( C_v \). Prior uncertainties with values smaller than \( \sigma_{\alpha_\parallel} \lesssim 0.05 \) and \( \sigma_{\alpha_\perp} \lesssim 0.01 \) provide sufficient precision that fluctuations in transmission do not dominate the uncertainties in the clustering, in which case a Ly\( \alpha \) galaxy survey could be used to measure cosmological parameters with a precision close to that available in a traditional galaxy redshift survey.

5.8 Comparison with previous HETDEX forecasts

Shoji et al. (2009) have presented forecasts for a galaxy redshift survey with parameters corresponding to HETDEX. Comparison with the results of their study serves both as a check of our analysis, and illustrates the relationship between the astrophysical parameters introduced through \( C_v, C_r \) and \( bC_v \), and the cosmological parameters \( \alpha_\parallel \) and \( \alpha_\perp \). The results from the analysis of Shoji et al. (2009) are listed in their table 1, and assume a value of bias \( b = 2.5 \), making the constraints directly comparable to this paper. First, our case of a traditional galaxy power spectrum should be compared to the constraints on \( \alpha_\parallel \) and \( \alpha_\perp \) obtained where constraints are marginalized only over the power-spectrum amplitude. Shoji et al. (2009) find \( \Delta \alpha_\parallel \approx 0.78 \) per cent and \( \Delta \alpha_\perp \approx 0.88 \) per cent in this case, which corresponds well to our values of 0.85 and 0.7 per cent.

In order to compare our results for a Ly\( \alpha \) selected galaxy redshift survey to the work of Shoji et al. (2009), we first consider the case of the limit where \( k\ell \ll 1 \), for which our power spectrum model is

\[ P_{Ly\alpha}(k, \mu) = P(k) [b + C_v + bC_v] + (1 - C_v) f \mu^2 \] .

Defining the power spectrum with a new bias parameter such that \( B \equiv (b + C_v + bC_v) \) and the Kaiser factor (Kaiser 1987) such that \( F \equiv (1 - C_v)f \), we obtain

\[ P_{Ly\alpha}(k, \mu) = P(k) [B + F \mu^2] \] ,

which is identical to the usual form. The modifications to the bias and Kaiser factor should therefore not affect the Alcock-Paczynski effect. However, the addition of transmission fluctuations means that constraints must be marginalized over the Kaiser factor, which changes the shape of contours.

This can be seen in fig. 3 of Shoji et al. (2009), where examples of constraints that include the cases of marginalization over amplitude, and also of marginalization over both amplitude and the Kaiser factor. Marginalizing over the Kaiser factor introduces additional uncertainty, with constraints of \( \Delta \alpha_\parallel \approx 1.13 \) per cent and \( \Delta \alpha_\perp \approx 1.10 \) per cent in this case. These values should be compared to our constraints of \( \Delta \alpha_\parallel \approx 1.1 \) per cent and \( \Delta \alpha_\perp \approx 0.9 \) per cent which are obtained with a broad prior on \( C_v \), but tight constraints on \( C_r \) (see Fig. 12). Finally, including the scale-dependent ionizing background term \( K(k) \) represents a similar effect to that of the primordial spectral index and its running. Shoji et al. (2009) presented constraints that included marginalizing over the amplitude, Kaiser factor and primordial power-spectrum shape, finding \( \Delta \alpha_\parallel \approx 1.36 \) per cent and \( \Delta \alpha_\perp \approx 1.23 \) per cent. These values are again very similar to our constraints without priors on \( C_r, C_v \) or \( C_v \) of \( \Delta \alpha_\parallel \approx 1.35 \) per cent and \( \Delta \alpha_\perp \approx 1.25 \) per cent.

Thus, the level at which transmission fluctuations will influence measurements of cosmological distance is comparable to those from
Figure 12. Constraints on power-spectrum distortions achievable via the Alcock–Paczynski test including prior constraints on $C_v$ and $bC_{\Gamma}$. Each panel shows contours of likelihood for the parameter set $(\alpha_{\perp}, \alpha_{\parallel})$, in the case of a Ly$\alpha$ galaxy power spectrum with $[C_v, bC_{\Gamma}, (b + C_{\rho})] = (0, 0, 2.5)$. Contours of likelihood for the values of $\alpha_{\parallel}$ and $\alpha_{\perp}$ are shown (at 61 per cent and 14 per cent of the peak likelihood). Prior likelihoods of $L_{C_v}(C_v) = \exp \left(-\frac{(C_v - \langle C_v \rangle)^2}{2\sigma_v^2}\right)$ and $L_{C_{\Gamma}}(bC_{\Gamma}) = \exp \left(-\frac{(bC_{\Gamma} - \langle bC_{\Gamma} \rangle)^2}{2\sigma_{b/Gamma_1}^2}\right)$ were included in the constraints. The four columns show constraints assuming $\sigma_v = 1, 0.05, 0.02$ and 0.01. For each of these columns, four rows are shown with $\sigma_{b/Gamma_1} = 1, 0.25, 0.1$ and 0.05. The 61 per cent contour for the traditional galaxy redshift survey constraints is plotted in each panel for comparison (thick dotted lines).

marginizing over other cosmological parameters. However, interpretations of measured quantities like the power-spectrum shape or the growth function $f$ will need to account for the astrophysical effects of Ly$\alpha$ transmission. For example, the possibility of a non-zero $C_v$ will complicate interpretation of the extracted value of the redshift distortion factor, because the measurement will be of $(1 - C_v)f$, rather than of $f$. This degeneracy will make it very difficult to test theories of modified gravity theory using the redshift space distortion (e.g. Blake et al. 2010).

6 CONSTRAINTS ON Ly$\alpha$ TRANSMISSION MODELS

We have shown that fluctuations in Ly$\alpha$ transmission will result in modification of the scale and angular dependence of the power spectrum measured from a large Ly$\alpha$ galaxy redshift survey like HETDEX. These modifications in the power spectrum potentially reduce the ability of the measured power spectrum to constrain cosmological parameters. On the other hand, our study also shows that the parameters describing the modifications to power spectrum are measured as part of the fitting process. Before concluding, we therefore calculate the available precision on the parameters $b + C_{\rho}$, $bC_{\Gamma}$ and $C_v$, whose values provide insight into the level of suppression of Ly$\alpha$ flux, and the astrophysics of the interaction between Ly$\alpha$ emitting galaxies and the IGM (Section 4).

In Fig. 13 we present constraints on the parameter sets $(C_v, bC_{\Gamma})$, $(C_v, b + C_{\rho})$ and $(bC_{\Gamma}, b + C_{\rho})$, in the case of a Ly$\alpha$ galaxy power spectrum with $[C_v, bC_{\Gamma}, (b + C_{\rho})] = (0, 0, 2.5)$. The numerical values of the measured uncertainties are listed in Table 3. These
The clustering of Lyα emitters

Figure 13. Constraints on the parameters \((b + C_p)\), \(C_r\) and \(C_v\) based on power-spectrum distortions. Uncertainties on the cosmology are included via the Alcock–Paczynski test. The left-hand, central and right-hand panels show contours of likelihood for the parameter sets \((C_v, bC_T)\), \((C_v, b + C_p)\) and \((bC_T, b + C_p)\), in the case of a Lyα galaxy power spectrum with \([C_v, bC_T, (b + C_p)] = (0, 0, 2.5)\). Contours of likelihood for the values of \(\alpha_L\) and \(\alpha_\perp\) are shown (at 61 and 14 per cent of the peak likelihood). We have included prior likelihoods of \(\mathcal{L}_{\alpha_L}(\alpha_L) = \exp\left(-\alpha_L^2/2\sigma_{\alpha_L}^2\right)\) and \(\mathcal{L}_{\alpha_\perp}(\alpha_\perp) = \exp\left(-\alpha_\perp^2/2\sigma_{\alpha_\perp}^2\right)\) to represent different precisions of knowledge of the cosmology at \(z = 2.5\). In the upper and lower panels, \(\Delta \alpha = \Delta \alpha_L = 0.05\) and \(\Delta \alpha = \Delta \alpha_\perp = 0.01\), respectively.

Table 3. Summary of constraints on \((b + C_p)\) \(bC_T\) and \(C_v\). The values of the fiducial model \((b + C_p)\), \(bC_T\) and \(C_v\), and the prior constraints \(\alpha_L\) and \(\alpha_\perp\) are listed.

| Fiducial model | Prior constraint | Lyα transmission constraints |
|----------------|------------------|-----------------------------|
| \(bC_T\)       | \(C_v\)          | \(\sigma_{\alpha_L}\) | \(\sigma_{\alpha_\perp}\) | \(\Delta(b + C_p)\) | \(\Delta(bC_T)\) | \(\Delta(C_v)\) |
| 0              | 0                | 0.01                       | 0.01                       | 0.013             | 0.15               | 0.025            |
| 0              | 0                | 0.05                       | 0.05                       | 0.017             | 0.19               | 0.040            |

constraints assume that the cosmological model is measured from other sources. The uncertainties in the cosmology are included in our analysis via the Alcock–Paczynski test (equation (42)), which for this application provides a measure of the uncertainty in the power-spectrum shape through the dilation parameters \(\alpha_L\) and \(\alpha_\perp\). An exception is the uncertainty in the mass power-spectrum amplitude (proportional to the normalization of the primordial power spectrum, \(\sigma_8\)) which is degenerate with \((b + C_p)\). Our analysis assumes that the shape of the primordial power spectrum and the value of \(f\) are known.

Using the power-spectrum sensitivity specified in equation (39), we construct likelihoods:

\[
\ln \mathcal{L}(p) = -\frac{1}{2} \sum_{k,\mu} \left[ \frac{P_{\text{obs}}(k, \mu)}{\Delta P_{\text{obs}}(k, \mu)} - P_{\text{obs}}(k, \mu) \right]_2^2 + \ln \mathcal{L}_{C_\parallel} + \ln \mathcal{L}_{C_\perp} + \ln \mathcal{L}_{C_T} + \ln \mathcal{L}_{\alpha_L} + \ln \mathcal{L}_{\alpha_\perp},
\]

where the sum is over bins of \(k\) and \(\mu\). We assume flat prior probabilities for the transmission-dependent parameters (i.e. \(\mathcal{L}_{C_\parallel} = \mathcal{L}_{C_\perp} = \mathcal{L}_{C_T} = \text{const}\)). To quantify the uncertainty, we have included prior likelihoods of \(\mathcal{L}_{\alpha_L}(\alpha_L) = \exp\left(-\alpha_L^2/2\sigma_{\alpha_L}^2\right)\) and \(\mathcal{L}_{\alpha_\perp}(\alpha_\perp) = \exp\left(-\alpha_\perp^2/2\sigma_{\alpha_\perp}^2\right)\). In the upper and lower panels of Fig. 13 we assume uncertainties of \(\sigma_{\alpha_L} = \sigma_{\alpha_\perp} = 0.05\) and \(\sigma_{\alpha_L} = \sigma_{\alpha_\perp} = 0.01\), respectively.

Given cosmological uncertainties \(\sigma_{\alpha_L} = \sigma_{\alpha_\perp} = 0.05\), we find that the values of \((b + C_p, bC_T\) and \(C_v\) could be constrained with precisions of \(\Delta(b + C_p) \sim \pm 0.02\), \(\Delta(bC_T) \sim \pm 0.25\) and \(\Delta C_v \sim \pm 0.04\). For next generation cosmological constraints with \(\Delta \alpha_L = \Delta \alpha_\perp = 0.01\), we find smaller errors on Lyα clustering parameters of \(\Delta(b + C_p) \sim \pm 0.015\), \(\Delta(bC_T) \sim \pm 0.15\) and \(\Delta C_v \sim \pm 0.02\).

These errors should be compared to the predicted values in Table 1, and with the results of Fig. 4. Since the measurement of non-zero values of the parameters \((b + C_p, bC_T\) or \(C_v\) indicates that the Lyα line is partially absorbed in the IGM (i.e. \(F > 0\) and \(\tau > 0\) in the analytic model), the available constraints in a survey like HETDEX could easily measure the presence of Lyα absorption in the IGM.

Of the available constraints, the parameter \((b + C_p)\) cannot be used to constrain transmission models despite the high precision with which it will be determined. This is because of the degeneracy between \(C_p\) and the unknown galaxy bias \(b\). Our models predict small values of \(bC_T\) (see Sections 3.5 and 4), except in very special cases, and so the available precision will not provide useful constraints. However, the precision \(\Delta C_p \sim \pm 0.04\) is small compared with expected values of \(C_p\) for a range of scenarios (Section 4, see also Zheng et al. 2011). In particular, the HETDEX survey could distinguish between infall- and outflow-dominated models of IGM transmission, for which the parameters range from 0.05 to 0.7. Measurement of this term would directly determine the extent to which the IGM impacts the observed flux, providing critical information on the intrinsic Lyα luminosity, and the presence of outflows.

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7 SUMMARY AND CONCLUSION

Wide-field searches are now finding Lyα emitters in large numbers, and these galaxies contribute greatly to our understanding of the star formation history, and of galaxy formation. In the near future, very large surveys of Lyα emitting galaxies will provide precision measurements of large-scale clustering at \( z \sim 2.5 \), and allow measurement of cosmological parameters at this previously unexplored epoch. However, to realize this goal it is crucial to understand the contribution to the observed clustering amplitude from fluctuations in intergalactic absorption of intrinsic Lyα flux. In this paper we have shown that the environmental dependence of Lyα absorption can lead to significant non-gravitational features in the redshift space power spectrum of Lyα galaxies, under a range of different physical scenarios. We have derived a physically motivated fitting formula that relates the scale- and direction-dependent Lyα power spectrum to the mass power spectrum [\( P(k) \)]:

\[
P_{\text{Lyα}}(k, \mu) = P(k) \times \left[ b \left( 1 + C_{f} \frac{\arctan(k\lambda)}{k\Delta_{1C}} \right) + C_{v} + (1 - C_{v}) f m \right]^{2}.
\]  

(48)

This formula can be used in the power-spectrum analyses of a galaxy redshift survey to account for the environmental dependence of Lyα absorption, which includes fluctuations in density, ionizing background and velocity gradient (parametrized by \( C_{f} \), \( C_{v} \) and \( C_{\rho} \), respectively). We have presented a simple analytic model to calculate the values of these parameters. Our calculations imply that standard Lyα absorption scenarios will yield values for \( C_{\rho} \), \( C_{v} \) and \( C_{f} \) that are at the tens of percent level, indicating that fluctuations in absorption of the Lyα line in the IGM can lead to modifications of the power spectrum of Lyα selected galaxies that are of order unity.

While our analytic model is useful for investigating the qualitative dependencies of clustering in Lyα selected galaxies, more detailed analyses are required to quantitatively predict the values of the constants \( C_{\rho} \), \( C_{v} \) and \( C_{f} \). To quantify the expected effect of fluctuations in Lyα absorption on the observed power spectrum, we have therefore employed previously published models of Lyα radiative transfer. These models explore the combined effects of local star formation and IGM infall, and galactic wind-driven outflows on the transmission of the Lyα line through the circumbulge IGM. We find that an infall-dominated model for Lyα transmission predicts significant contributions (of order unity) to the observed power spectrum. On the other hand, an outflow-dominated model for Lyα transmission predicts contributions to the observed power spectrum that are of order magnitude smaller, at the level of \( \sim 5-10 \) per cent.

We have shown that the expected non-zero values of \( C_{\rho} \), \( C_{v} \) and \( C_{f} \) will complicate attempts to use the clustering of Lyα emitters to constrain cosmological parameters in very large-scale surveys. To quantify the influence of Lyα absorption on the ability of a large Lyα galaxy survey to constrain cosmological parameters, we have applied our modified redshift space power spectrum to a survey with parameters corresponding to the planned HETDEX. We considered both cosmological constraints obtained from the BAO scale, and from the full shape of the power spectrum as measured by the Alcock–Paczynski effect. To baseline our study we also consider the case of a traditional galaxy redshift survey where the probability of galaxy selection is not a function of environment. Our analysis shows that a survey with the parameters of HETDEX could measure the BAO scale along and transverse to the line of sight with precisions of \( \sim 3 \) and \( \sim 2 \) per cent, respectively. We find that this precision is unaffected by modifications to the power spectrum that arise from fluctuations in Lyα absorption. This finding is consistent with previous studies which have shown that sources of scale-dependent bias can be removed in order to correctly recover the BAO scale.

For a traditional galaxy redshift survey with the volume and galaxy density of HETDEX, much tighter constraints are available through consideration of the full power-spectrum shape (Shoji et al. 2009). In this case, we find that the Alcock–Paczynski effect could be used to constrain both the line-of-sight and transverse directions at better than the 1 per cent level for a traditional galaxy redshift survey in which the shape of the primordial power spectrum and the growth function \( f \) are known. However, our analysis shows that the dependence of observed Lyα flux on velocity gradient and ionizing background has the potential to compromise the cosmological information available from the full power-spectrum shape measured in a Lyα selected galaxy redshift survey. In a scenario where there is no prior knowledge of the details of Lyα absorption in the IGM, we find the precision of line of sight and transverse distance measurements the HETDEX would be decreased by a factor of 1.5–2, from \( \sim 0.8 \) per cent in the case of a traditional galaxy redshift survey to \( \sim 1.3–1.7 \) per cent. The weakened constraints on \( \alpha \) and \( \alpha_{\perp} \) arise because Lyα transmission fluctuations introduce scale and angular dependencies into the power spectrum that are degenerate with those of an incorrect cosmology. In particular, the effect of a fluctuating ionizing background on the shape of the observed power spectrum of Lyα selected galaxies is similar to that of an uncertainty in the shape of the primordial power spectrum, while fluctuations in velocity gradient have an effect that is similar to that of redshift space distortions.

We also investigated the precision with which modelling of the Lyα radiative transfer must be understood in order for HETDEX to achieve a goal of better than 1 per cent distance measurements based on Lyα galaxy clustering. We find that as the prior precision on \( C_{f} \) is increased, the accuracy with which \( \alpha_{\parallel} \) is measured also increases. As the prior precision on \( C_{f} \) is increased, the strength of the correlation between \( \alpha_{\parallel} \) and \( \alpha_{\perp} \) is increased. However increased precision in \( \alpha_{\parallel} \) requires prior knowledge of both \( bC_{v} \) and \( C_{\rho} \). Prior uncertainties with values smaller than \( \Delta C_{\parallel} \lesssim 0.05 \) and \( \Delta C_{\rho} \lesssim 0.01 \) provide sufficient accuracy that fluctuations in transmission do not dominate the uncertainties in the clustering. In such cases, a Lyα galaxy survey could be used to measure cosmological parameters with a precision comparable to a traditional galaxy redshift survey of equivalent volume and number density. On the other hand, these uncertainties are at a level below the accuracy with which \( C_{\rho} \), \( C_{v} \) and \( C_{f} \) can be reliably predicted based on current theoretical understanding.

We have turned the above analysis around and assumed instead that the cosmology is known a priori from other sources. The clustering of Lyα emitters can then be used to measure the impact of the IGM on observed Lyα lines, and to infer the properties of the Lyα transmission model. Our models predict small values of \( C_{f} \), and so the precision available from a survey like HETDEX (\( \Delta C_{f} \sim \pm 0.15–0.25 \)) will not provide useful constraints. However, the precision \( \Delta C_{v} \sim \pm 0.02–0.04 \) would be small compared with the expected values for a range of scenarios (Section 4). For example, clustering of Lyα galaxies could distinguish between infall- and outflow-dominated models of IGM transmission. Measurement of this term in a survey like HETDEX would therefore directly determine the extent to which the IGM impacts the observed flux, providing information on the kinematics of the cold gas through which the Lyα photons are scattering.
The nature of Ly$\alpha$ emitters, their role in galaxy formation, and their utility as probes of cosmology, and of the state of the IGM and ISM are important topics to which large ongoing observational programs promise to make significant contributions. In this paper we have shown that power-spectrum measurements from a very large survey of Ly$\alpha$ selected galaxies could be used to study the relationship between the observed Ly$\alpha$ flux, and the astrophysics of the galaxy–IGM connection. However, we also show that Ly$\alpha$ transmission fluctuations decrease the cosmological precision of a galaxy redshift survey by a factor of 1.5–2 relative to the best case precision available in a traditional galaxy redshift survey. Realizing the full cosmological potential of a survey like HETDEX will therefore require a much more detailed theoretical understanding of the astrophysics that determines the relationship between the observed and intrinsic Ly$\alpha$ flux. Our study underlines the need for continued work to understand the role of radiative transfer through the IGM and ISM in determining the observed properties of Ly$\alpha$ emission.

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