EXTENDED Ly$\alpha$ EMISSION AROUND STAR-FORMING GALAXIES

ZHENG ZHENG$^1$, RENYUE CEN$^2$, DAVID WEINBERG$^3$, HY TRAC$^4$, AND JORDI MIRALDA-ESCUDE$^5$,$^6$

$^1$ Yale Center For Astronomy and Astrophysics, Yale University, New Haven, CT 06520, USA; zheng.zheng@yale.edu
$^2$ Department of Astrophysical Sciences, Princeton University, Peyton Hall, Ivy Lane, Princeton, NJ 08544, USA
$^3$ Department of Astronomy, Ohio State University, Columbus, OH 43210, USA
$^4$ Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15213, USA
$^5$ Institut Catalana de Recerca i Estudis Avançats, Barcelona, Spain
$^6$ Institut de Ciències del Cosmos, Universitat de Barcelona, Barcelona, Spain

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ABSTRACT

Ly$\alpha$ photons that escape the interstellar medium of star-forming galaxies may be resonantly scattered by neutral hydrogen atoms in the circumgalactic and intergalactic media, thereby increasing the angular extent of the galaxy’s Ly$\alpha$ emission. We present predictions of this extended, low surface brightness Ly$\alpha$ emission based on radiative transfer modeling in a cosmological reionization simulation. The extended emission can be detected from stacked narrowband images of Ly$\alpha$ emitters (LAEs) or of Lyman break galaxies (LBGs). Its average surface brightness profile has a central cusp, then flattens to an approximate plateau beginning at an inner characteristic scale below \sim 0.2 Mpc (comoving), then steepens again beyond an outer characteristic scale of ~1 Mpc. The inner scale marks the transition from scattered light of the central source to emission from clustered sources, while the outer scale marks the spatial extent of scattered emission from these clustered sources. Both scales tend to increase with halo mass, UV luminosity, and observed Ly$\alpha$ luminosity. The extended emission predicted by our simulation is already within reach of deep narrowband photometry using large ground-based telescopes. Such observations would test radiative transfer models of emission from LAEs and LBGs, and they would open a new window on the circumgalactic environment of high-redshift star-forming galaxies.

Key words: cosmology: observations – galaxies: halos – galaxies: high-redshift – galaxies: statistics – intergalactic medium – large-scale structure of universe – radiative transfer – scattering

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1. INTRODUCTION

High-redshift star-forming galaxies are becoming an important probe of galaxy formation, reionization, and cosmology. Ionizing photons of young stars in star-forming galaxies ionize neutral hydrogen atoms in the interstellar medium (ISM), and each subsequent recombination has a probability of \sim 2/3 of ending up as a Ly$\alpha$ photon (Partridge & Peebles 1967). After escaping the ISM, these Ly$\alpha$ photons can be scattered by neutral hydrogen atoms in the circumgalactic and intergalactic medium (IGM), which tends to make the Ly$\alpha$ emission extended. In this paper, we present predictions for the extended Ly$\alpha$ emission associated with high-redshift star-forming galaxies from a radiative transfer model of Ly$\alpha$ emission applied to a hydrodynamic cosmological simulation (Zheng et al. 2010).

As a result of reprocessed ionizing photons, prominent Ly$\alpha$ emission can be a characteristic of star-forming galaxies, which can be used to detect high-redshift galaxies. Galaxies detected through the strong Ly$\alpha$ emission associated with them (e.g., from narrowband photometry) are dubbed Ly$\alpha$ emitters (LAEs) and an increasing number of such galaxies have been discovered (e.g., Hu & McMahon 1996; Cowie & Hu 1998; Rhoads et al. 2003; Malhotra & Rhoads 2004; Gawiser et al. 2007; Ouchi et al. 2008; Guaita et al. 2010; Ouchi et al. 2010). High-redshift star-forming galaxies can also be detected from broadband photometry with the Lyman break technique, which are termed Lyman break galaxies (LBGs; e.g., Steidel et al. 2003). As long as Ly$\alpha$ photons reprocessed from ionizing photons can escape from the ISM, Ly$\alpha$ emission is also expected to be associated with LBGs. Ly$\alpha$ emission encodes useful information about star-forming galaxies and their environments, such as star formation rate (e.g., Madau et al. 1998), kinematics of ISM gas (e.g., Steidel et al. 2010), and neutral fraction of IGM gas (e.g., Dijkstra et al. 2007). Ly$\alpha$ photons usually experience complex radiative transfer processing (resonant scatterings) in media with neutral hydrogen atoms, which complicates the interpretation of observed Ly$\alpha$ emission properties.

Zheng et al. (2010, hereafter Paper I) present a physical model of Ly$\alpha$ emission from LAEs by solving Ly$\alpha$ radiative transfer in the circumgalactic and intergalactic media. The Ly$\alpha$ radiative transfer calculation is performed in a cosmological volume (100 h$^{-1}$ Mpc on a side) from a state-of-the-art radiation-hydrodynamic reionization simulation (Trac et al. 2008). The calculation uses a 768$^3$ grid to sample the density, velocity, and temperature of the neutral hydrogen gas in the simulation and is applied to all the sources residing in halos above 5 \times 10^7 h^{-1} M_\odot. Resonant scatterings enable Ly$\alpha$ photons to probe the circumgalactic and intergalactic environments (density and velocity structures) around star-forming galaxies. This leads to a coupling between the observed Ly$\alpha$ emission properties and the environments. This simple physical model is able to explain an array of observed properties of z \sim 5.7 LAEs in the Subaru/XMM-Newton Deep Survey (SXDS; Ouchi et al. 2008), including Ly$\alpha$ spectra, morphology, apparent Ly$\alpha$ luminosity function (LF), shape of the ultraviolet (UV) LF, and the distribution of Ly$\alpha$ equivalent widths. The selection imposed by the environment-dependent radiative transfer also introduces interesting new features in the clustering of LAEs (Zheng et al. 2011, hereafter Paper II).

In the above radiative transfer model, while the number of Ly$\alpha$ photons is conserved after they escape the ISM, the scatterings in the circumgalactic and intergalactic media cause the Ly$\alpha$
emission to spread spatially. Therefore, one generic prediction of the model is an extended \( \text{Ly}\alpha \) emission halo around a star-forming galaxy. Observationally, only a fraction of \( \text{Ly}\alpha \) photons can be detected for an individual source, those included in the central part of the extended \( \text{Ly}\alpha \) emission with high enough surface brightness (tip of the iceberg). The outskirts of the \( \text{Ly}\alpha \) halo with low surface brightness is typically buried in the sky noise.

In this paper, we show that it is possible to detect the bottom of the iceberg by stacking the narrowband images of a large number of sources to suppress the sky noise. We present the predictions of the extended \( \text{Ly}\alpha \) emission in the stacked image from our radiative transfer model and discuss what we can learn from it. Our radiative transfer modeling is performed for sources at \( z \approx 5.7 \). We study properties of the \( \text{Ly}\alpha \) surface brightness profile from stacked images in Section 2. In Section 3, we discuss the observational prospects. We summarize our results in Section 4.

Throughout the paper, we adopt a spatially flat \( \Lambda \)CDM cosmological model for our calculations, with a matter density parameter \( \Omega_m = 0.28 \) and a Hubble constant \( h = 0.70 \) in units of \( 100 \text{ km s}^{-1} \text{ Mpc}^{-1} \). Distances are expressed in comoving units unless otherwise mentioned explicitly.

2. EXTENDED \( \text{Ly}\alpha \) EMISSION AROUND STAR-FORMING GALAXIES

The \( \text{Ly}\alpha \) radiative transfer calculation in Paper I is performed in a simulation box of \( 100 \text{ h}^{-1} \text{ Mpc} \) (comoving) on a side with the neutral hydrogen density, temperature, and peculiar velocity sampled with a \( 768^3 \) grid. The cell size is therefore \( 130.2 \text{ h}^{-1} \text{ kpc} \) (comoving), about the virial diameter of a \( 10^{11} \text{ M}_\odot \) halo. The star-forming region in a high-redshift galaxy, where \( \text{Ly}\alpha \) photons in our study originate, is only a few kpc (comoving) across (e.g., Taniguchi et al. 2009). So the initial \( \text{Ly}\alpha \) emission is treated as a point source at the halo center for the purpose of the radiative transfer calculation. The size of the pixel for collecting \( \text{Ly}\alpha \) photons is eight times finer, corresponding to \( 16.3 \text{ h}^{-1} \text{ kpc} \) (comoving) or 0.58. With the cell resolution, the gas distribution is uniform inside the virial radius of small halos (below a few times \( 10^{10} \text{ h}^{-1} \text{ M}_\odot \)), which would have some effect on the \( \text{Ly}\alpha \) surface brightness profile. However, since \( \text{Ly}\alpha \) photons are initially emitted from a point source and the dynamics of the infall region around halos play a significant role in determining the distribution of \( \text{Ly}\alpha \) photons (Paper I), the resolution we use is sufficient for obtaining the generic features in the extended \( \text{Ly}\alpha \) emission. We present a resolution test in Section 2.5, and the main results presented in this paper would remain valid with improved resolution. Our calculation does not address the effects of galactic wind and dust, and we discuss these model uncertainties in Sections 2.4 and 3.

2.1. Stacked \( \text{Ly}\alpha \) Image and \( \text{Ly}\alpha \) Emission at Fixed Halo Mass

We start from the stacked \( \text{Ly}\alpha \) image for sources residing in halos of fixed mass, \( 10^{11} \text{ h}^{-1} \text{ M}_\odot \). In our model, the intrinsic \( \text{Ly}\alpha \) luminosity, which is the total amount of \( \text{Ly}\alpha \) emission from the reprocessed ionizing photons, is tightly correlated with the halo mass; therefore this stacking is basically for sources at fixed intrinsic \( \text{Ly}\alpha \) luminosity or UV luminosity.

Our radiative transfer model produces a three-dimensional array, recording the \( \text{Ly}\alpha \) spectra as a function of spatial position on the sky. We construct the narrowband \( \text{Ly}\alpha \) image from this array, with a filter width similar to that in the \( z \approx 5.7 \) SXDS (see Paper I). Our simulation box has about the same area as SXDS with a redshift depth three times larger. So we are able to construct narrowband \( \text{Ly}\alpha \) images for three SXDS-like fields. Each image corresponds to an ideal case with perfect continuum and sky subtraction. Examples of images of individual sources can be found in Paper I (Figures 4 and 5). We stack all the source images together as would be done with the narrowband observation. For each source, the image includes the center and surrounding pixels (up to a radius of \( \sim 10 \text{ h}^{-1} \text{ Mpc} \)). The center pixel is chosen to be the one that contains the halo center. It is evident that the surrounding pixels can include \( \text{Ly}\alpha \) photons from other neighboring sources. For all the sources in a narrow bin (0.16 dex) of halo mass around \( 10^{11} \text{ h}^{-1} \text{ M}_\odot \) (about 440 sources for each of the SXDS-like fields), we stack their images with their centers aligned.

Typically there are two algorithms to generate a stacked image, taking either the mean or the median. The stacked \( \text{Ly}\alpha \) image from the mean algorithm is shown in Figure 1. The mean algorithm has the advantage of conserving the flux, even though it may be affected by outliers in the flux distribution, showing up as many small clumps in the stacked image. The median stacked image has the advantage of insensitivity to outliers. We find that at a fixed projected radius, the observed flux roughly follows a log-normal distribution among different sources, which causes the surface brightness from the median stacked image to be lower in amplitude than that from the mean stacked image (see solid curves in Figure 2). The stacking cases mentioned above correspond to an ideal situation of no photon noise. When total photon noise (source + sky) is added, the surface brightness profile from the mean stacked image remains the same and that from the median stacked image would change. In the limit of large noise (compared to the signal distribution), the flux distribution is completely modified by the noise distribution, and the median value is driven to be close to the mean (see also Pieri et al. 2010). In practice, the large noise limit is typical at large radii for the case considered here (see below), so the surface brightness profile from the median stacked image approaches that from the mean stacked one. See the thin solid curve in Figure 2. In what follows, we focus on presenting our results from the mean stacked image. We compute the surface brightness profile by averaging the flux in annuli at different radii so that the effect of the grainy feature seen in the image is greatly reduced.
The surface brightness profile from the stacked image shows a few interesting features. It has two characteristic scales that are associated with steep changes in the profile slope. The inner slope change occurs at $R_{in} \sim 0.1 h^{-1}\text{Mpc}$ (possibly an upper limit, see Section 2.5) and the outer one at $R_{out} \sim 1 h^{-1}\text{Mpc}$. Inside the inner characteristic radius $R_{in}$, the profile appears as a central cusp, roughly following a steep power law. Between the inner and outer characteristic radii, $R_{in} < R < R_{out}$, the surface brightness decreases slowly with increasing radius, close to a plateau. Beyond the outer characteristic radius $R_{out}$, the surface brightness profile steepens and drops, forming an extended tail. As shown later, the two scales have clear physical meanings.

With the mean surface brightness profile, we compute the cumulative luminosity as a function of projected radius (bottom panel of Figure 2). It turns out that the luminosity from the stacked image does not converge at large radius. Because of the plateau in the surface brightness profile, the luminosity profile approximately follows $R^2$, a trend similar to that from the global mean surface brightness (dot-dashed line). The global mean profile is computed by uniformly distributing the total Ly$\alpha$ flux in the original narrowband image across the whole image. The plateau in the stacked surface brightness profile has a much higher amplitude than the global mean. As we show later, the higher signal is caused by the clustered neighboring sources.

In the top panel of Figure 2, we also show the level of sky noise (dotted lines). The calculation is based on a 4 hr observation with the NB816 filter using the Subaru telescope,\(^7\) which is roughly the setup for the survey of $z \sim 5.7$ LAEs in SXDS (Ouchi et al. 2008). In the NB816 band, the sky (AB magnitude of 20.4 mag arcsec$^{-2}$ in a dark night) has a surface brightness of $f_{sky} \sim 1.36 \times 10^{15}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. The mean sky photon count in a 2$''$ diameter aperture from a 4 hr exposure with the Subaru telescope reaches $N_{sky} \sim 7.1 \times 10^3$. Therefore, the 1$\sigma$ sky noise in a 2$''$ diameter aperture corresponds to a surface brightness level of $f_{sky}/\sqrt{N_{sky}} \sim 5.1 \times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, which is higher than the signal of interest on large scales (Figure 2). The noise per pixel is expected to be suppressed by $\sqrt{N}$ with $N$ sources stacked. The suppression works even better for detecting the signal at large radii, because the annulli used to compute the mean surface brightness profile can be much larger than the 2$''$ aperture. Within each annullus, however, the noise in different pixels is correlated, since the same pixel from the original image may fall into the annullus several times from centering different sources. The correlations need to be accounted for in estimating the noise level at each radius for the stacked profile. In practice, given the low surface brightness of the extended Ly$\alpha$ emission and the high sky noise level, stacking the image before subtracting the continuum and sky may help to reduce errors caused by such subtraction and to increase the sensitivity.

### 2.2. Decomposition of the Ly$\alpha$ Surface Brightness Profile in the Stacked Image

To understand the features in the stacked Ly$\alpha$ surface brightness profile and the origin of the two characteristic scales, we perform a test by assigning artificial surface brightness profiles for individual sources. The image of each source (in halos above $5 \times 10^5 h^{-1} M_\odot$) is assumed to be a circular disk of radius $R_0$ with uniform surface brightness normalized such that the total luminosity is the intrinsic Ly$\alpha$ luminosity from the source. That is, we replace the intrinsic point source with a uniform “seeing” disk or (equivalently) modify it by a top-hat point-spread function (PSF). We then follow the same procedure as above to form the stacked image for sources in $10^{11} h^{-1} M_\odot$ halos and derive the Ly$\alpha$ surface brightness profile. No radiative transfer is performed in this artificial model, and we use it to illustrate the effect of source extent combined with source clustering.

Figure 3 shows the series of surface brightness profiles with different “seeing” disk radii $R_0$. For a small “seeing” disk radius ($R_0 = 0.08 h^{-1}\text{Mpc}$), sources are close to point-like. The central spike (inside $R_0$) is clearly seen in the profile from the stacked image. Outside of this radius, we still see signals, which are obviously contributed from neighboring sources as a result of clustering.

\(^7\) We use the Subaru Imaging Exposure Time Calculator at http://www.naoj.org/cgi-bin/img_etc.cgi.
The two-dimensional two-point correlation function (essentially the two-halo term. Source, these photons still belong to the contribution from the Lyα and stacked). Even though neighboring sources can have their profile is defined as the Lyα (see below). We emphasize that the one-halo term in the stacked profile of individual sources (the one-halo term). For simplicity, Equation (1) assumes that $\Sigma$ depends only on halo mass, while in reality it depends on the environment around halos as well (see below). We emphasize that the one-halo term in the stacked profile is defined as the Lyα emission from the central source alone (i.e., contributed from all the sources to be center-aligned and stacked). Even though neighboring sources can have their Lyα photons scattered into the one-halo scales of the central source, these photons still belong to the contribution from the two-halo term.

In the limit of compact sources (small $R_s$ in the uniform “seeing” disk case), $\Sigma_{1h}$ can be replaced with $L(M')\delta_D(R - R')$, where $L(M')$ is the intrinsic Lyα luminosity and $\delta_D$ is the Dirac delta function. The two-halo term then becomes

$$\Sigma_{2h}(R | M) = \int dM' \frac{dN}{dM'} \int d^2\theta' \times [1 + w(R | M, M')]\Sigma_{1h}(R - R' | M'),$$

where $dN/dM'$ is the surface number density of halos, $w$ is the two-dimensional two-point correlation function (essentially the angular correlation function), and $\Sigma_{1h}$ is the surface brightness profile of individual sources (the one-halo term). For simplicity, Equation (1) assumes that $\Sigma_{1h}$ depends only on halo mass, while in reality it depends on the environment around halos as well (see below). We emphasize that the one-halo term in the stacked profile is defined as the Lyα emission from the central source alone (i.e., contributed from all the sources to be center-aligned and stacked). Even though neighboring sources can have their Lyα photons scattered into the one-halo scales of the central source, these photons still belong to the contribution from the two-halo term.

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$$\Sigma_{2h}(R | M) = \int dM' \frac{dN}{dM'} L(M')[1 + w(R | M, M']).$$

For the small “seeing” disk case in Figure 3 ($R_s = 0.08 h^{-1} \text{Mpc}$), the flattening below $0.3 h^{-1} \text{Mpc}$ is a sign of the halo exclusion effect, which leads to a zero signal in the three-dimensional two-point correlation function and a constant in the angular two-point correlation function $w$. According to Equation (2), we expect to see a flattened profile on large scales, where $w \ll 1$. On these scales, which are out of the range of the plot, it is hard in practice to disentangle such a uniform background from the sky background. We therefore limit ourselves to the regime where $w$ is still large.

By varying the radius $R_s$ of the uniform “seeing” disk, we show the effect of the spatial extent of the Lyα emission on the surface brightness profile from the stacked image (Figure 3). As the “seeing” disk size increases, the two-halo term of the profile is smoothed on scales below the “seeing” disk size, which results in a decrease in the amplitude. In our setup, the uniform “seeing” disk has a surface brightness of $1.4 \times 10^{-19}(R_s/0.4 h^{-1} \text{Mpc})^{-2} \text{erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2}$ for $R < R_s$, which is by definition the one-halo term contribution. However, the small-scale surface brightness (in the one-halo regime) in Figure 3 decreases more slowly than $R_s^{-2}$, as a consequence of the contribution from the smoothed two-halo term. For $R_s = 1.6 h^{-1} \text{Mpc}$, the signal is already dominated by the two-halo term on all scales. The approximate plateau seen in the stacked profile from the radiative transfer model (thick solid curve) is close to the case with a “seeing” disk size of $R_s = 1.6 h^{-1} \text{Mpc}$. The test suggests that the plateau feature between the two characteristic scales mainly originates from spatially extended, scattered Lyα emission from clustered sources around the central source.

The uniform “seeing” disk only gives us a rough idea of the features in the extended Lyα emission. To be more accurate, we need to examine the Lyα surface brightness profile of individual sources.

As an example, we show in Figure 4 the surface brightness profiles of one individual source in the simulation box from the radiative transfer model. The two curves correspond to the profiles viewed along different directions, and the difference reflects the environment-dependent Lyα radiative transfer, as discussed in detail in Paper I. The surface brightness has a steep drop below $0.3 h^{-1} \text{Mpc}$. Then it levels off until a cutoff is reached around $2-3 h^{-1} \text{Mpc}$. The inner surface brightness profile of one source goes roughly as $R^{-2}$ and the luminosity increases logarithmically with radius. Most of the luminosity comes from near the cutoff radius at $\sim 2 h^{-1} \text{Mpc}$, which is the reason why the plateau up to such a scale in the total profile is produced (see below).

As discussed in Paper I, the shape of the surface brightness profile largely depends on the velocity field. Below $0.3 h^{-1} \text{Mpc}$, the contribution to the surface brightness profile comes mainly from the Lyα photons that are last scattered in the infall region around the halo. On larger scales, where the profile levels off, the last scattering of Lyα photons occurs in the IGM that undergoes Hubble flow. The cutoff radius corresponds to those photons that are the bluest after escaping the infall region. They can travel far away from the source before being redshifted into the line center.

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8 The bump around $0.3 h^{-1} \text{Mpc}$ can be understood as follows. Roughly speaking, $w(R) \propto \int_{-\infty}^{\infty} 1(R, \xi z) d\xi$ with $z = \sqrt{r_c^2 - R^2}$ in the regime that $R < r_c$, where $r_c \sim 0.2-0.3 h^{-1} \text{Mpc}$ is the halo exclusion scale and $\xi$ is the three-dimensional two-point correlation function (zero on scales below $r_c$). As $R$ increases, the competition between a decreasing $\xi$ on average and an increasing path length of integration (i.e., a decreasing lower limit $z_0$) leads to a small bump in $w$ around $0.3 h^{-1} \text{Mpc}$. If the seeing disk is comparable or larger than the size of the halo (e.g., the $R_s = 0.2 h^{-1} \text{Mpc}$ case in Figure 3 for $10^{11} h^{-1} M_\odot$ halos), the bump is smeared out.
to be significantly scattered in the IGM. The exact shape of the surface brightness profile also depends on the initial frequency of Ly$\alpha$ photons (see Section 2.4).

As emphasized in Papers I and II, Ly$\alpha$ radiative transfer depends on circumgalactic and intergalactic environments (density and velocity structures). Even for sources in halos of the same mass, there is a broad distribution of environments. Therefore, the one-halo term of the surface brightness profile is not identical for sources in halos of fixed mass or for the same source viewed along different directions (Figure 4). The one-halo term in Equation (1) should have a dependence on environment in addition to halo mass. To obtain the mean one-halo term for the stacked image and decompose the surface brightness profile, we perform Ly$\alpha$ radiative transfer calculations separately for each source with halo mass in the $10^{11} h^{-1} M_{\odot}$ mass bin. We then stack the individual one-halo terms to obtain the mean.

The dotted curve in Figure 5 is the mean one-halo term for sources in $10^{11} h^{-1} M_{\odot}$ halos. The shape is similar to that seen in Figure 4. The dashed curve is the two-halo term, inferred from subtracting the one-halo term from the total surface brightness profile. The two-halo term can be expressed as a convolution (Equation (1)), with the convolution kernel being the one-halo term of the clustered star-forming halos of all masses. The shape of the one-halo term at different halo mass is similar to that shown in Figure 5. In the two-halo term, a plateau reaches out to a radius of 1–2 $h^{-1}$ Mpc, which is around the cutoff scale of the mass-averaged one-halo term. This is not a coincidence. The scale where the plateau in the two-halo term ends marks the spatial extent of the extended Ly$\alpha$ emission of the clustered sources, since on scales larger than this the smoothing effect from the source PSF is small. As the two-halo term dominates on large scales, the above scale is just the outer characteristic scale $R_{\text{out}}$ seen in the total surface brightness profile. The inner characteristic scale $R_{\text{in}}$ marks the transition from the one-halo term dominated regime to the two-halo term dominated regime. The realistic decomposition of the surface brightness profile confirms the results of the test in Figure 3 that the origin of the plateau between the two characteristic scales in the total surface brightness profile is the extended Ly$\alpha$ emission.

The environment-dependent Ly$\alpha$ radiative transfer couples the observed Ly$\alpha$ emission with the circumgalactic and intergalactic environments. Many consequences of such a coupling are studied in Papers I and II. For the stacked surface brightness profile, the environment dependence also appears, as detailed below.

At fixed halo mass, which corresponds to fixed intrinsic Ly$\alpha$ luminosity or UV luminosity in our model, the observed Ly$\alpha$ luminosity has a broad distribution, reflecting the distribution of environments. In our model, for each source we link together the pixels above a surface brightness threshold similar to that used in Ouchi et al. (2008) to define the observed emission, and if none of the pixels around the central source exceeds the threshold, we simply take the flux in the pixel at the source position as the observed emission (see Paper I for details). The observed luminosity is only a fraction of the extended Ly$\alpha$ emission, coming from the central, high surface brightness part of the source. The one-halo term of the surface brightness profile is expected to be closely related to the environment.

We divide the sources into two samples of equal size, according to the observed Ly$\alpha$ luminosity. In Figure 6, we show the stacked surface brightness profiles for the bright and faint halves. The dotted curves show the corresponding one-halo terms. We note that the fluxes inferred from the one-halo terms of the two cases are not necessarily the same. The reason is that the scattered emission is not isotropic, being sensitive to the density and velocity structures around the source. Overall, the sample of sources with lower observed Ly$\alpha$ luminosity has a shallower stacked surface brightness profile at small radius and there is no clear scale of the transition from the inner cusp to the approximate plateau. The result implies that the stacked Ly$\alpha$ narrowband image for star-forming galaxies with weaker observed Ly$\alpha$ emission would appear to be less compact.

2.3. Dependence on UV and Ly$\alpha$ Luminosity

So far we have focused on the Ly$\alpha$ surface brightness profile for sources in halos of $10^{11} h^{-1} M_{\odot}$. The profile is expected to be a function of the halo mass. We show the dependence on halo mass in Figure 7, for both halos in narrow mass bins (left panel) and above different mass thresholds (right panel). Since in our model the UV luminosity is tightly correlated with halo mass,
Figure 6. Surface brightness profile of extended Ly$\alpha$ emission from stacked narrowband image as a function of observed Ly$\alpha$ luminosity. All sources reside in halos of $10^{11} h^{-1} M_{\odot}$. Thin (thick) curves are for the faint (bright) half of the sources based on the observed Ly$\alpha$ luminosity, which is contributed by the central, high surface brightness region. Dotted curves are the corresponding one-halo profiles. See the text for details.

The amplitude of the stacked profile increases with halo mass. On small scales this increase is largely a reflection of the fact that halos of higher masses host sources of higher Ly$\alpha$ luminosity, while on large scales there is an additional contribution from stronger source clustering around more massive halos.

On small scales (inside the inner characteristic radius), where the one-halo profile makes a substantial contribution, sources in higher mass halos show a steeper profile. The inner characteristic scale $R_{in}$, where the profile starts to level off, increases with halo mass. This implies that sources in higher mass halos have more extended Ly$\alpha$ emission. The outer characteristic scale $R_{out}$, where the profile starts to steepen again, also increases with halo mass. As discussed above, this scale is an indication of the spatial extent of the Ly$\alpha$ emission of the clustered sources. Massive halos are typically located in dense environments, and therefore the clustered sources around them tend to be in massive halos as well. On scales larger than $R_{out}$, the extended tail of the profile for higher mass halos is steeper. This is also a consequence of the higher clustering amplitude, since the surface brightness profile is proportional to $(1+w)$ as in Equation (1), and the factor of unity tends to flatten the profile for weakly clustered sources.

Overall, the stacked Ly$\alpha$ surface brightness profile is steeper for sources in higher mass halos, and the two characteristic scales increase with halo mass. On small scales where the central cusp dominates, if we approximate the profile by a power law, we find that the power-law index decreases with halo mass, ranging from $-0.5$ to $-1.4$ (from $-0.5$ to $-1.7$) for the mass bin (threshold) samples shown in Figure 7.

The halo mass (UV luminosity) sequence does not have a priori selection based on observed Ly$\alpha$ emission, so it applies to the case of LBGs.

In practice, the brightness profile that can be easily measured in a narrowband survey is the stacked image of the identified LAEs, classified according to their apparent (observed) Ly$\alpha$ flux. Figure 8 shows the stacked Ly$\alpha$ surface brightness profile for LAEs as a sequence of the apparent (observed) Ly$\alpha$ luminosity for both luminosity bin samples (left panel) and luminosity threshold samples (right panel).

The apparent Ly$\alpha$ luminosity couples to the circumgalactic and intergalactic environments around sources as a result of the Ly$\alpha$ radiative transfer, which imposes a strong selection effect for sources that are identified as LAEs. On small scales (inside $R_{in}$), the stacked profile for LAEs appears to be steeper than those seen in cases in Figure 7 for sources without Ly$\alpha$ selection. In Figure 8, the central cuspy profile has a slope of $-0.9$ to $-1.8$ ($-1.1$ to $-1.8$) for luminosity bin (threshold) samples, with steeper slopes for higher observed Ly$\alpha$ luminosities. The amplitude increases with the apparent Ly$\alpha$ luminosity. On scales above the inner characteristic scale, the amplitude also increases with Ly$\alpha$ luminosity, but the dependence is much weaker. This weak dependence is a consequence of the weak dependence of the projected clustering on apparent Ly$\alpha$ luminosity, as discussed in Paper II. There is also a trend that the two characteristic scales increase with the apparent Ly$\alpha$ luminosity, but it is much weaker than that seen in Figure 7 for LBGs.

Figure 7. Dependence of mean Ly$\alpha$ surface brightness profile on host halo mass (or UV luminosity). Left: profiles for samples of galaxies in different bins of halo mass. From bottom to top curves, host halo mass increases from log$[M/h^{-1} M_{\odot}] = 9.8$ to 11.8, with an interval of 0.2 dex between two adjacent curves. Right: similar to the left panel, but for samples of galaxies in halos above different mass thresholds.
2.4. Dependence on the Intrinsic Lyα Line Profile

In all our discussions above, the intrinsic Lyα line profile is assumed to be Gaussian with the width determined by velocity dispersion in the halo (Paper I). More specifically, the standard deviation of the Gaussian profile is set to equal the one-dimensional thermal velocity dispersion for gas in the halo, \( \sigma = 31.9 \left[ \frac{M_b}{10^{10} \, M_\odot} \right]^{1/3} \, \text{km s}^{-1} \). As discussed in Papers I and II, the intrinsic line profile is one of the main uncertainties in our radiative transfer modeling. The spatial extent of the Lyα emission depends on the initial line profile. For example, in the extreme case where all the Lyα photons are shifted far to the red from the line center within the emitting galaxy (e.g., as a possible consequence of a strong galactic wind; Dijkstra & Wyithe 2010), they would not be further scattered in the surrounding medium and the Lyα emission would not extend beyond the size of the galaxy.

To test the effect of the initial line profile on the spatial distribution of Lyα photons, we perform radiative transfer calculations with different initial values of Lyα wavelength for an individual source in a halo of \( 10^{11} \, h^{-1} \, M_\odot \) (the same source as in Figure 4). Figure 9 shows the Lyα surface brightness and cumulative luminosity profiles for cases with different initial line shifts (in units of the thermal velocity dispersion \( \sigma \) mentioned above).

On average, bluer photons travel farther in the IGM before they redshift into the line center to encounter significant scatterings. Therefore, the Lyα emission would dilute to a larger spatial extent. This is clearly seen in Figure 9—the spatial distribution becomes more and more extended as the initial Lyα wavelength shift varies from \(-3 \sigma\) to \(-9 \sigma\). If we start with red Lyα photons, the final Lyα surface brightness profile becomes more compact. In Figure 9, the intrinsic Lyα luminosity for all curves is the same. The surface brightness curves for initially red photons appear to be of lower amplitude, because they have a central spike (within \( 0.02 \, h^{-1} \, \text{Mpc}\) that is not shown in the left panel. The contribution of the central spike to the total luminosity can be figured out from the cumulative luminosity curves shown in the right panel. Overall, the Lyα emission appears to be close to point-like if photons start from the far red side of the line center. These red photons can still have a probability of experiencing resonant scatterings in the infall region around the halo and being shifted to the blue side. The surface brightness profile on scales \( \lesssim 1 \, h^{-1} \, \text{Mpc}\) is expected to be contributed by these photons. The probability of such scatterings depends on the magnitude of the shift and the infall velocity around the halo. For sources in \( 10^{11} \, h^{-1} \, M_\odot \) halos, even with a +3\( \sigma\) initial line shift (thin dashed curves in Figure 9), the flattening part in the surface brightness profile can still be clearly seen (left panel), although the majority of the observed Lyα photons are from the central region (right panel). We verify that for a +3.5\( \sigma\) initial line shift (not shown in the plot) the contribution from the central region to the total Lyα luminosity is \( \lesssim 40\%\), less than that from the extended emission. If we take this as a threshold for the profile to change from point-like to extended, it would correspond to \( \sim 250 \, \text{km s}^{-1}\).

If the wavelength shift of the initial Lyα photons is in the range of \( \pm 3 \sigma\), the resultant surface brightness distribution is not sensitive to the initial Lyα wavelength, as shown by the solid curves in Figure 9. This is easy to understand: photons starting at a wavelength shift \( \pm 3 \sigma\) undergo many scatterings in the core, leading to a distribution that loses memory of the original wavelength and to a nearly constant surface brightness profile. But photons with a larger initial wavelength deviation are not scattered enough times to be redistributed in this way before they escape. Therefore, the predicted Lyα profile should be reliable except when many photons are emitted from the central galaxy with a wavelength shift of several times the velocity dispersion.

To eliminate most of the extended Lyα emission around the galaxies, the initial line shifts (after photons escape the ISM) need to be larger than \( 250 \, \text{km s}^{-1}\) for halos of \( 10^{11} \, h^{-1} \, M_\odot\). Galactic winds can have the effect of shifting Lyα emission toward red (e.g., Verhamme et al. 2006; Dijkstra & Wyithe 2010). From observations of \( z \sim 3\) galaxies, Steidel et al. (2010) find that the interstellar absorption line shifts with respect to the Hα-defined galaxy systemic redshift by \( 165 \pm 140 \, \text{km s}^{-1}\) (mean \( \pm \) standard deviation) for galaxies of baryon mass (stars plus cold gas) ranging from \( \sim 1 \times 10^{10} M_\odot\) to \( \sim 3 \times 10^{11} M_\odot\). The uncertainty in velocity measured for individual galaxies is estimated to be \( \sim 130 \, \text{km s}^{-1}\). If the wind is confined in a region not far from the ISM, the above observational results indicate that the initial shift in Lyα emission could be above \( \sim 300 \, \text{km s}^{-1}\). However, even in such a case, the shift may not
be sufficient for Ly\(\alpha\) photons to completely decouple from the circumgalactic and intergalactic environments, depending on the spatial distribution of the wind. Observationally, the outflowing neutral gas of the wind is not isotropic, usually collimated in a spatial distribution of the wind. Observationally, the outflowing circumgalactic and intergalactic environments, depending on the be sufficient for Ly\(\alpha\) photons, so we expect that the grid resolution in our calculation is able to predict the generic features in the extended Ly\(\alpha\) emission. We perform a resolution test to show that this is the case.

It would be ideal to do such a test with a higher resolution grid. However, the available reionization simulation outputs prevent us from doing this. Therefore, we degrade the default 768\(^3\) grid used in this paper to a lower resolution 384\(^3\) grid by binning the gas density, temperature, and peculiar velocity. We then perform the Ly\(\alpha\) radiative transfer calculation with such a grid for 10\(^{11}\)\(\, M_\odot\) halos and compare the resultant average Ly\(\alpha\) surface brightness profile (the one-halo term) with that with the 768\(^3\) grid.

The comparison is shown in Figure 10. For each resolution case, the thin and thick arrows mark the half and full size of a grid cell, respectively. For a source located at the center of a cell, the initial Ly\(\alpha\) photons see a uniform gas distribution within a radius of about half cell size. However, the final Ly\(\alpha\) surface brightness distribution inside this resolution radius is determined by the gas properties not only in this central cell but also in the surrounding cells. The reason is that Ly\(\alpha\) photons propagating into surrounding cells have chances to be scattered back into the central cell. That is, the surface brightness profile is not a local quantity as a result of radiative transfer. Therefore, the small-scale surface brightness profile (in particular the slope) is not completely a result of the grid resolution, as indicated by the fact that the power-law-like inner profile naturally extends to scales a few times larger than the resolution scale. The transition to a plateau is not an artifact of grid resolution either.

With the low-resolution grid, the general features in the Ly\(\alpha\) surface brightness profile remain the same: a steep drop on small scales and an extended plateau on large scales before a sharp cutoff. However, the amplitude of the profile on small scales is about a factor of two higher with the low-resolution grid, and it is compensated by a slightly lower amplitude on large scales. Therefore, a lower resolution has the effect of making the emission more concentrated.

If the grid were a factor of two finer than the default grid, we expect the predicted small-scale surface brightness profile to be

2.5. Effect of Grid Resolution

For the main results in this paper, our Ly\(\alpha\) radiative transfer calculation is performed in a 100\(^3\)\(\, h^{-1}\)\(\, \text{Mpc}^3\) simulation box, where gas properties (density, temperature, and peculiar velocity) are sampled with a 768\(^3\) grid. All Ly\(\alpha\) photons are originally emitted from point sources and the scatterings of Ly\(\alpha\) photons inside individual cells are also followed. As shown in Paper I, the dynamics of the infall region around halos play a significant role in determining the distribution of Ly\(\alpha\) photons, so we expect the predicted Ly\(\alpha\) luminosity for all cases is normalized to be the same.
lower and the difference should be smaller than a factor of two. The Ly$\alpha$ emission would become more extended. We therefore expect that the generic prediction of the extended Ly$\alpha$ emission would be strengthened with an improved grid resolution.

Even though for the one-halo term of the surface brightness profile the overall cusp-to-plateau behavior does not depend on the grid resolution, the transition scale decreases for a higher resolution. Figure 10 seems to show that the transition happens at a scale about twice the cell size, indicating a resolution effect. Although cells around the source cell contribute to the determination of the profile of the central cusp, the cuspy profile itself is inevitably expected to also depend on the exact density, temperature, and velocity distributions of neutral gas within the source cell. The effects discussed in Section 2.4 add further uncertainties in the cuspy profile.

Despite the above uncertainties, our prediction on the existence of the extended Ly$\alpha$ emission around high-redshift star-forming galaxies remains valid, as long as Ly$\alpha$ photons encounter scatterings in the circumgalactic and intergalactic media. The predicted two characteristic scales in the surface brightness profile from stacked images should be regarded as an upper limit.

3. DISCUSSION

The Ly$\alpha$ emission from star-forming galaxies is extended because of resonant scattering in the circumgalactic and intergalactic environments. In the stacked narrowband Ly$\alpha$ image, the change from a declining to a nearly flat surface brightness profile at a characteristic scale of a few tenths of a Mpc (possibly an upper limit, see Section 2.5) and that from the flat profile to a declining profile at a few Mpc are evidence for the resonant scattering nature of the extended Ly$\alpha$ emission.

According to our radiative transfer modeling, the visibility of Ly$\alpha$ emission from star-forming galaxies depends on the circumgalactic and intergalactic environments around sources, and only the central, high surface brightness part can be detected as LAEs. The extended Ly$\alpha$ emission around the star-forming galaxies is predicted to exist (as long as Ly$\alpha$ photons escape from the ISM), no matter whether they can be detected as LAEs or not. This implies that the extended emission can be detected from both LBGs and LAEs. In practice, to detect the extended Ly$\alpha$ emission around LAEs, we need to know their redshifts and take their Ly$\alpha$ narrowband images. Extended Ly$\alpha$ emission from LAEs is more readily detected, since LAEs are typically discovered in narrowband surveys.

Our radiative transfer modeling is performed for $z = 5.7$ star-forming galaxies. The generic picture should remain valid at other redshifts—as long as Ly$\alpha$ photons encounter significant scatterings in the circumgalactic/intergalactic medium, the Ly$\alpha$ emission would become extended. However, the physical conditions in and around star-forming galaxies evolve with redshift. For example, compared to $z = 5.7$ galaxies, we expect a lower neutral hydrogen density around $z \sim 3$ galaxies, as a result of the expansion of the universe and the evolution of the UV background. The Hubble expansion rate decreases, a change that may partially compensate the decrease in neutral density for Ly$\alpha$ scattering. The extended Ly$\alpha$ emission (e.g., the surface brightness profile) at $z \sim 3$ may not follow the details of our $z = 5.7$ prediction, although it is expected to show up. We reserve the investigation of the redshift dependence of the extended Ly$\alpha$ emission for future work. We do not include dust in our model. The effect of ISM dust on the Ly$\alpha$ line depends on whether the dust distribution is clumpy or not (Neufeld 1991; Hansen & Oh 2006). Optical, UV, and Ly$\alpha$ observations of local star-forming galaxies show evidence that ISM kinematics and geometry play a more significant role than dust in affecting the Ly$\alpha$ emission (e.g., Giavalisco et al. 1996; Keel 2005; Atek et al. 2008, 2009). We also expect the dust content to decrease toward high redshift (e.g., $z \sim 6$), and there is observational evidence for low dust content in $z \gtrsim 6$ galaxies (e.g., Bouwens et al. 2010; Ono et al. 2010). It is likely, however, that the existence of dust can lead to variations in the amount of Ly$\alpha$ photons escaping from the ISM, and thus add additional scatter in the extended Ly$\alpha$ emission among individual galaxies. Keeping all the above caveats in mind, we discuss the current status of observing the extended Ly$\alpha$ emission.

Observations have long been suggesting the existence of extended Ly$\alpha$ emission. Based on Hubble Space Telescope (HST) broadband and New Technology Telescope (NTT) narrowband images, Moller & Warren (1998) found that three LBG-like galaxies near a $z = 2.8$ quasar are more extended in Ly$\alpha$ emission (half-light radius of 0.5′−0.7′) than in the continuum (half-light radius of 0.1′). Observations with NTT and Very Large Telescope (VLT) of a larger sample of LAEs (~70) in quasar fields at $z \sim 3$ further strengthen the case for extended Ly$\alpha$ emission (e.g., Fynbo et al. 2001, 2003; also see Laursen & Sommer-Larsen 2007 for a comparison of one of their objects with the results from a model with Ly$\alpha$ radiative transfer). In particular, Fynbo et al. (2001) found the size of Ly$\alpha$ emission to be 0.65 (FWHM) in the stacked narrowband images of seven LAEs. Although the spatial extent of the Ly$\alpha$ emission from the
above observations is small compared to what we predict, owing to the surface brightness detection limit, it is clear that Ly$\alpha$ emission is more extended than the underlying UV emission.

There are efforts to use stacked narrowband images in deep surveys to study the compactness of the Ly$\alpha$ emission. Hayashino et al. (2004) find that 24 spectroscopically confirmed $z \sim 3$ LBGs in Steidel et al. (2003) fall within the redshift range of their deep narrowband image observed with the Subaru telescope (with only two of them being identified as LAEs). The UV luminosity of these LBGs ranges from $-20$ mag to $-22.5$ mag (based on the observed $R_{AB}$ magnitude; Steidel et al. 2003). After removing two gigantic Ly$\alpha$ blobs, the composite narrowband (continuum subtracted) image of the 22 LBGs shows Ly$\alpha$ emission that extends at least to 5$''$ (about 0.1 h$^{-1}$ Mpc comoving; see their Figure 8). The surface brightness drops from $\sim 3 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ at $\sim 1''$ to a few times $\sim 3 \times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ at $\sim 4''$, corresponding to a power-law index of $\sim -1.7$. They further note that 13 LBGs with no individual detection of extended Ly$\alpha$ emission also show extended Ly$\alpha$ emission on their composite image. The findings of Hayashino et al. (2004) are in line with our prediction that extended Ly$\alpha$ emission exists for LBGs, and the slope of the surface brightness profile is also in broad agreement with our prediction for UV bright sources.

Steidel et al. (2011) present the result of a stacking analysis of deep narrowband observations of 92 UV continuum-selected star-forming galaxies at $2.2 < z < 3.1$. Some sources are the same ones as in Hayashino et al. (2004) but with much deeper narrowband observation. The stacked narrowband image shows diffuse Ly$\alpha$ emission around star-forming galaxies, with surface brightness drops from a few $\times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ at the center to $\sim 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ at a radius of $\sim 1''$ ($\sim 80$ proper kpc). The extended emission exists in the stacked image of sub-samples—LBGs, LAEs, and Ly$\alpha$ absorbers all show qualitatively similar diffuse emission. The overall surface brightness amplitude of the extended emission increases with the central Ly$\alpha$ emission. Although the redshift difference prevents us from a direct comparison between the observation and our prediction, the detected diffuse Ly$\alpha$ emission supports our generic picture that resonant scatterings in the circumgalactic and intergalactic media cause Ly$\alpha$ emission originating from star formation in the central galaxy to become extended. If we make a naive comparison, the Ly$\alpha$ emission is detected up to the inner characteristic scale in the surface brightness profile (e.g., Figures 7 and 8), not reaching the plateau yet. In Steidel et al. (2011), the clustered sources are intentionally masked before image stacking, which may change the shape of the plateau if it could be detected. We plan to extend our model to $z \sim 3$ star-forming galaxies and make direct comparison with the observation in Steidel et al. (2011).

Ono et al. (2010) use stacked multiband images of LAEs at $z \sim 5.7$ and 6.6 in the SXDS to investigate the stellar population of LAEs. For the narrowband stacked images, they find that the Ly$\alpha$ fluxes level off for apertures larger than 5$''$ in diameter. Such a behavior in the surface brightness profile is predicted in our model as the transition to the two-halo term dominated regime. It is likely that the feature seen by Ono et al. (2010) is caused by the clustering of Ly$\alpha$ emitting sources.

Finkelstein et al. (2011) detect Ly$\alpha$ emission from three spectroscopically confirmed $z = 4.4$ LAEs in the HST/ACS F658N narrowband imaging data. They find that Ly$\alpha$ emission appears to be more extended than the UV emission. However, the half-light radii of Ly$\alpha$ emission are quite small, in the range of 0.1$''$–0.2$''$. One thing to notice is that the observation is not deep enough to reach the sensitivity to detect the much larger extended Ly$\alpha$ halo predicted by our model. This is clear from the fact that the surface brightness level in the HST narrowband observation turns out to be above a few times $10^{-16}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. It is also supported by the fact that the three objects have significantly higher Ly$\alpha$ fluxes detected from ground-based narrowband images (with larger telescope apertures and reduced sensitivity to read noise; Finkelstein et al. 2011). With HST/WFPC2 narrowband images of eight $z = 3.1$ LAEs, Bond et al. (2010) find half-light radii of Ly$\alpha$ emission to be in a similar range, 0.15$''$–0.30$''$. The surface brightness level (a few times $10^{-17}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$) reached by the observation is still too high to probe the extended Ly$\alpha$ emission predicted by our model.

Extended Ly$\alpha$ emission can also be detected through deep spectroscopic observations. Rauch et al. (2008) conduct a long-slit search for $2.67 < z < 3.75$ low surface brightness Ly$\alpha$ emission from a 92 hr long exposure with the VLT, reaching a 1$\sigma$ surface brightness detection limit of $8 \times 10^{-20}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ in a 1 arcsec$^2$ aperture. They find 27 objects with possible Ly$\alpha$ emission lines. These objects are typically fainter than the LAEs and LBGs in Steidel et al. (2011). About one-third of them show clear signatures of extended emission. If the surface brightness profile at large radii is approximated by a power law, the slope is generally in the range of $-1$ to $-3$ (their Figure 17). In the stacked surface brightness profile (their Figure 20), the emission clearly extends to $\gtrsim 4''$ (about comoving 90 h$^{-1}$ kpc), dropping from $\sim 8 \times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ at a radius of 1$''$ to $\sim 1 \times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ at large radii. The profile roughly follows a power law with an index in the range of $-1.5$ to $-2.0$. This is in the ballpark of the predicted extended emission, although a direct comparison is not possible because of the redshift difference. The spatially resolved spectra of the extended emission remain as an interesting aspect to be explored in our model.

The extended Ly$\alpha$ halo from Ly$\alpha$ scatterings predicted by our model shares some similarities with the one around a quasar before reionization described in Loeb & Rybicki (1999). Unlike Loeb & Rybicki (1999), who assume a uniform, zero-temperature IGM undergoing Hubble expansion, we use a realistic distribution of gas density, temperature, and velocity around a star-forming halo from a cosmological reionization simulation. We expect that extended Ly$\alpha$ emission around star-forming galaxies also exists before reionization, which merits further study. However, the Ly$\alpha$ surface brightness is expected to be proportional to the source luminosity and to not depend on the neutral fraction in the IGM as long as the majority of photons are scattered, while it should decline with redshift as $(1 + z)^{-4}$, making the detection increasingly difficult at higher redshift.

Our radiative transfer calculation is done for sources residing in halos above $5 \times 10^9 h^{-1} M_\odot$. Star formation in lower mass halos, down to $\sim 2 \times 10^8 h^{-1} M_\odot$ at $z \sim 5.7$ (with virial temperature $> 10^4$ K for gas to cool; see Trac & Cen 2007), can also contribute to the two-halo term of the stacked profile. According to Trac & Cen (2007, see their Figure 1), the total star formation rate in $< 5 \times 10^9 h^{-1} M_\odot$ halos can contribute about two-thirds of the global rate. The amplitude of the clustering...
with these low mass halos is lower, and we expect that including the Ly\(\alpha\) emission from the \(<5 \times 10^7 h^{-1} M_\odot\) halos would boost the two-halo term of the surface brightness profile presented in this paper at the factor of two level and that the two characteristic scales would shift inward. Our model does not resolve subhalos, but we do not expect a large subhalo (or satellite galaxy) fraction for galaxies at redshift \(z \sim 6\). If we consider a mass threshold sample of halos with \(M_h > M_{\text{min}}\) and assume that the mean number of subhalos increases linearly with halo mass as \(M_h/(10 M_{\text{min}})\) (Kravtsov et al. 2004), we find that the satellite fraction is about 15\% for \(M_{\text{min}} \sim 10^{11} h^{-1} M_\odot\). As subhalos are distributed inside the virial radius of the parent halo, including star formation in subhalos would make the central cuspy surface brightness profile in the stacked image more extended, which would smooth the transition to the plateau part of the profile and increase the inner characteristic scale. Investigating the exact magnitude of the effect is beyond the scope of this paper.

Besides star formation, there are other sources of Ly\(\alpha\) emission that increase in the dense regions around galaxies, including fluorescence from the UV background and cooling radiation. At \(z \sim 5.7\), the fluorescent emission caused by the UV background is expected to be at the level of a few times \(10^{-21} \text{erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2}\) (e.g., Gould & Weinberg 1996; Kollmeier et al. 2010), much fainter than the signal of interest in this paper. Cooling radiation may have a noticeable contribution to the stacked Ly\(\alpha\) surface brightness profile, but there are uncertainties in the theoretical prediction (e.g., Faucher-Giguère et al. 2010). Further work is needed to see whether Ly\(\alpha\) emission from cooling radiation can change the profile and to see how one can separate Ly\(\alpha\) emission caused by star formation from other sources of Ly\(\alpha\) emission.

Finally, for observational efforts, sky subtraction is an important step in revealing the extended Ly\(\alpha\) emission from star-forming galaxies. To compare the observation with the theoretical prediction from simulations, a detailed description of the method of sky subtraction used in the observation is necessary, which should be reproduced in the same way in the model.

4. CONCLUSION

After escaping from the ISM, Ly\(\alpha\) photons converted from ionizing photons in star-forming galaxies experience scatterings in the circumgalactic and intergalactic media. Such a radiative transfer process makes Ly\(\alpha\) emission from these galaxies spatially extended. In this paper, built on the radiative transfer modeling of LAEs in Zheng et al. (2010, 2011), we investigate the predicted spatial distribution of Ly\(\alpha\) emission that can be measured from the stacked narrowband image of these galaxies.

In general, the predicted surface brightness profile measured from the stacked image has two characteristic scales: an inner one at tenths of a Mpc and an outer one at about 1 Mpc. The profile shows a central cusp inside the inner scale, an approximate plateau between the two scales, and an extended tail beyond the outer scale. The inner scale may possibly be an upper limit, as an effect of the grid resolution in the simulation (see Section 2.5).

The stacked surface brightness profile can be understood as a superposition of the brightness distribution from the stacked sources themselves (one-halo term) and that from neighboring clustered sources (two-halo term). The two-halo term is the profile of the (angular) two-point correlation function (plus one) smoothed by the extended Ly\(\alpha\) emission profile (PSF) of individual sources. The smoothing makes the profile flattened on scales smaller than the spatial extent of Ly\(\alpha\) emission of clustered sources. The outer characteristic scale in the stacked surface brightness profile marks this spatial extent, and the plateau in the profile is a consequence of the smoothing effect.

The transition from one-halo term domination to two-halo term domination leads to the inner characteristic scale seen in the stacked surface brightness profile.

For continuum-selected galaxies (LBGs), the amplitude of the stacked Ly\(\alpha\) surface brightness profile increases with the source UV luminosity (or halo mass) on both small and large scales. The two characteristic scales also increase with the UV luminosity. The central cusp becomes steeper for higher UV luminosity. For Ly\(\alpha\) line-selected galaxies (LAEs), the amplitude of the central cuspy profile increases with observed Ly\(\alpha\) luminosity and the slope is steeper than that of LBGs. Beyond the inner characteristic scale, the amplitude of the surface brightness profile only has a weak dependence on observed Ly\(\alpha\) luminosity. The inner and outer characteristic scales do not show strong dependence on Ly\(\alpha\) luminosity either.

Because of the contribution from source clustering to the stacked surface brightness profile, the cumulative Ly\(\alpha\) luminosity from the stacked image does not converge to the intrinsic Ly\(\alpha\) luminosity of the stacked sources. It is therefore not straightforward to estimate the total Ly\(\alpha\) emission from the stacked image.

In detail, the surface brightness profile depends on the initial line profile of Ly\(\alpha\) emission (after Ly\(\alpha\) photons escape the ISM). The source would appear to be more compact in the narrowband image as the initial line shift toward red increases. If this shift is caused by galactic wind, the wind velocity needs to be comparable to a few times the virial velocity of the host halo and the wind needs to be largely isotropic to make Ly\(\alpha\) emission point-like. Conversely, from the measured Ly\(\alpha\) surface brightness profile in the narrowband image, it may be possible to constrain the effect of galactic winds. It is worth further study along this line.

Our particular prediction here is for sources after reionization is complete (\(z \sim 5.7\)). It is interesting to investigate how the prediction changes for star-forming galaxies at lower redshifts, because of the large effort to observe star-forming galaxies around redshift 2–4 (e.g., Rauch et al. 2008; Steidel et al. 2011) and in the local universe (e.g., Kunth et al. 2003; Hayes et al. 2007; Östlin et al. 2009). It is also necessary to study the extended emission for sources at higher redshifts, before reionization is complete, given the increasing observational efforts (e.g., Ouchi et al. 2010; Kashikawa et al. 2011).

At the time of our initial submission, we conclude that deep narrowband photometry from large ground-based telescopes is on the verge of detecting the extended Ly\(\alpha\) emission around star-forming galaxies, including LBGs and LAEs (e.g., Hayashino et al. 2004; Ono et al. 2010). Now the latest observation by Steidel et al. (2011) indeed revealed the extended Ly\(\alpha\) emission to large radii (~10” around) LBGs and LAEs, starting to verify our prediction and provide a stringent test of the theoretical model. The detection of the predicted Ly\(\alpha\) emission supports the generic picture that Ly\(\alpha\) radiative transfer in the circumgalactic and intergalactic environments produces extended Ly\(\alpha\) emission. The extended Ly\(\alpha\) emission opens a new window to study the circumgalactic and intergalactic environments of high-redshift star-forming galaxies. The surface brightness profile encodes information about cold baryons around galaxies, including their density, temperature, and velocity. All of these properties could be modified by galactic wind, so the extended emission in principle can put constraints on the galactic wind.
The stacked Ly$\alpha$ image also includes contributions from faint galaxies that cannot be detected in a single exposure, which provides an opportunity to study low-luminosity star-forming galaxies. The extended emission gives us a better idea on the total amount of Ly$\alpha$ emission from galaxies. When compared with the UV emission or other optically thin line emission (e.g., H$\alpha$ emission), we may infer the dust distribution and its effect on Ly$\alpha$ photons. With integral-field-units observations of high-redshift star-forming galaxies, we would have stacked spectra for the extended emission and expect to learn more about galaxy environments. Details on how to extract all the information encoded in the extended Ly$\alpha$ emission need to be investigated, and Ly$\alpha$ radiative transfer calculation, in combination with sophisticated models of star-forming galaxies and their environments, will play an irreplaceable role.

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