Evidence for Large-scale Fluctuations in the Metagalactic Ionizing Background Near Redshift Six

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Abstract

The observed scatter in intergalactic Lyα opacity at z ≤ 6 requires large-scale fluctuations in the neutral fraction of the intergalactic medium (IGM) after the expected end of reionization. Post-reionization models that explain this scatter invoke fluctuations in either the ionizing ultraviolet background (UVB) or IGM temperature. These models make very different predictions, however, for the relationship between Lyα opacity and local density. Here, we test these models using Lyα-emitting galaxies (LAEs) to trace the density field surrounding the longest and most opaque known Lyα trough at z < 6. Using deep Subaru Hyper Suprime-Cam narrowband imaging, we find a highly significant deficit of z ≈ 5.7 LAEs within 20 h⁻¹ Mpc of the trough. The results are consistent with a model in which the scatter in Lyα opacity near z ~ 6 is driven by large-scale UVB fluctuations, and disfavor a scenario in which the scatter is primarily driven by variations in IGM temperature. UVB fluctuations at this epoch present a boundary condition for reionization models, and may help shed light on the nature of the ionizing sources.

Key words: dark ages, reionization, first stars – galaxies: high-redshift – intergalactic medium – quasars: absorption lines

Supporting material: machine-readable table

1. Introduction

The characteristics of the high-redshift intergalactic medium (IGM) are a key diagnostic of cosmic reionization and the growth of the first galaxies. The temperature, ionization state, and density distribution of the IGM at z ≥ 5 reflect the impact of galaxies on their environments at early times. Spatial fluctuations in IGM properties, moreover, may reflect the late-time impact of inhomogeneous reionization.

One of the most striking features of the IGM at these redshifts is the presence of large-scale fluctuations in Lyα opacity. Fan et al. (2006) noted these fluctuations in measurements of the effective optical depth (τ_eff = −ln(T)), where T is the continuum-normalized transmission) in the Lyα forest toward 19 z ~ 6 quasars (see also Djorgovski et al. 2006). The scatter was confirmed in further measurements by Becker et al. (2015) and Bosman et al. (2018), with the most extreme example being a giant “Gunn-Peterson” trough spanning 110 h⁻¹ Mpc toward the z = 6.0 quasar ULAS J0148+0600 (herein J0148). Although the scatter in opacity due to variations in the density field can become large when the mean opacity is high (Lidz et al. 2006), the range in Lyα opacity on 50 h⁻¹ comoving Mpc scales near z ~ 6 significantly exceeds the scatter expected due to the density field alone (Becker et al. 2015). Large-scale, order unity variations in the hydrogen neutral fraction must therefore be present at these redshifts, in stark contrast to the roughly uniform neutral fraction (averaged over large scales) generally assumed for the IGM at later times.

In a photoionized IGM, the hydrogen neutral fraction, f_HІ, scales as

\[ f_{HI} \propto n_H T^{-0.7} \Gamma^{-1}, \]

where \( n_H \) is the total hydrogen density, \( T \) is the gas temperature (which impacts the recombination rate), and \( \Gamma \) is the photoionization rate. If density fluctuations alone are insufficient to produce the observed range in Lyα opacity, then large-scale variations in temperature and/or photoionization rate must be present. Over the past few years, multiple models have invoked such fluctuations to explain the wide distribution of Lyα opacities near z ~ 6. Davies & Furlanetto (2016) proposed that fluctuations in a galaxy-dominated ionizing ultraviolet background (UVB) may be present due to spatial variations in the mean free path of ionizing photons. Chardin et al. (2015, 2017) also proposed that the wide \( \tau_{eff} \) distribution may be due to UVB fluctuations, but attributed the fluctuations to a radiation field dominated by rare, bright sources such as quasars. On the temperature side, D’Aloisio et al. (2015) proposed that large temperature fluctuations may be present following an extended reionization epoch that ended not long before z = 6.

Intriguingly, each of these models poses challenges for conventional IGM models. In the Davies & Furlanetto (2016) UVB model, the typical mean free path must be at least a factor of three shorter than what would be predicted from extrapolations of lower-redshift measurements (Worseck et al. 2014, and references therein). The evolution of the global ionizing emissivity may also be unphysically rapid over 5 < z < 6, unless estimates at z ~ 5 are too low due to biases in the measured mean free path (D’Aloisio et al. 2018). The Chardin et al. (2015, 2017) model requires a number density of quasars at the high end of observational constraints (Giallongo et al. 2015; McGreer et al. 2018). A UVB dominated by quasars may also cause helium in the IGM to fully reionize too early (D’Aloisio et al. 2017). This could violate evidence from the He II Lyα forest that helium reionization ends near z ~ 3 (e.g., Worseck et al. 2011, 2016), and produce IGM temperatures that exceed current constraints near z ~ 4–5 (Becker et al. 2011). Finally, the temperature model requires...
both an extended, late reionization history and a local temperature boost from reionization that is at the upper end of physically motivated values (McQuinn 2012). It is uncertain, moreover, whether sufficient temperature fluctuations can be produced in radiative transfer simulations of reionization that are consistent with IGM temperature measurements at z < 5 (Keating et al. 2018; but see Upton Sanderbeck et al. 2016). Clearly, determining the origin of the τeff fluctuations would shed new light on the physics governing the high-redshift IGM.

Recently, Davies et al. (2018) showed that the competing models could be tested by probing the relationship between Lyα opacity and local environment (see also D’Aloisio et al. 2018). Specifically, the galaxy UVB model of Davies & Furlanetto (2016) predicts that a deep Lyα trough such as the one toward J0148 should arise in voids, where the UV background is suppressed. The temperature model of D’Aloisio et al. (2015), in contrast, predicts that troughs should occur in high-density regions that reionized early and have had sufficient time to cool. Davies et al. (2018) suggested that galaxies along the quasar line of sight could be used to probe the density field. Observationally, this test requires (i) identifying galaxies within the redshift range of the trough, (ii) sufficient sensitivity that the galaxies will adequately sample the underlying density field, and (iii) a survey area that is large enough to cover the region of interest around the quasar line of sight, and ideally a surrounding region that can be used for a self-consistent comparison.

In this paper we report on a survey for Lyα-emitting galaxies (LAEs) in the field of J0148 using Hyper Suprime-Cam (HSC) on the Subaru telescope. The HSC data have sufficient areal coverage and depth to conduct the experiment proposed by Davies et al. (2018). In addition, the LAE candidates are selected using the NB816 narrowband filter, whose central wavelength conveniently sits right in the middle of the J0148 trough (Figure 1). We present our HSC data in Section 2. The selection of LAE candidates is described in Section 2.3, and the results are compared to model predictions in Section 3.2. Finally, we summarize our results and discuss caveats to the interpretation in Section 4. Throughout the paper we assume a ΛCDM cosmology with Ωm = 0.3, ΩΛ = 0.7, Ωb = 0.048, and σ8 = 0.82, and quote distances in comoving units. All magnitudes are in the AB system.

Figure 1. X-Shooter spectrum of the z = 6.0 quasar ULAS J0148+0600, from Becker et al. (2015). The black line is centered on the Lyα forest and includes the ~110 h−1 Mpc Lyα absorption trough spanning 7930 Å < λ < 8360 Å. Corresponding redshifts are shown along the top axis. The blue line, offset by 0.1 in normalized flux, is shifted in wavelength to show the Lyβ forest at the same redshifts. The red line shows the HSC NB816 filter curve.

Table 1
Imaging Data Summary

| Filter | texp (hr) | Seeing (arcsec) | m5 | PSF | CModel |
|--------|----------|----------------|----|-----|--------|
| r2     | 1.5      | 0.62           | 26.5 | 27.5 | 27.4   |
| i2     | 2.4      | 0.64           | 26.0 | 27.0 | 26.9   |
| NB816  | 4.5      | 0.60           | 25.3 | 26.3 | 26.1   |

Notes.

a Median seeing FWHM across all source positions in the combined mosaic.
b Magnitude at which 50% of detected sources detected have S/N > 5. Values are given for fluxes in 1′′5 circular apertures, as well as for PSF and CModel fluxes.

2. Data

2.1. Hyper Suprime-Cam Imaging

We acquired deep HSC imaging of the field around J0148 from 2016 September and 2017 August, with the majority of data obtained in 2017. Imaging was performed in the r2, i2, and NB816 filters in dithered exposures centered on the quasar position. Total exposure times are listed in Table 1. The NB816 filter has a transmission-weighted mean wavelength of λ = 8177 Å, corresponding to Lyα at z = 5.726, and ≥50% peak transmission over 8122 Å < λ < 8239 Å, corresponding to 5.681 < z < 5.777.

The data were processed using the LSST Science Pipeline4 Version 13, release w_2017_28 (Axelrod et al. 2010; Jurić et al. 2015), with an implementation closely following the HSC Software Pipeline described in Bosch et al. (2018). The pipeline processes the individual CCDs and combines them into stacked mosaics. Pan-STARRS1 DR1 imaging (Chambers et al. 2016) was used for photometric and astrometric calibration. The pipeline also estimates the seeing parameters as a function of position. The median seeing in all bands was roughly 0′′6 (Table 1).

The LSST pipeline performs a range of photometric measurements. For our analysis we used forced measurements, wherein the intrinsic spatial parameters of a source are determined from the band in which it is detected with the highest significance (typically NB816 for our sources). These

4 https://pipelines.lsst.io
parameters are then held fixed for other bands, and the model profile is convolved with the local point-spread function when measuring fluxes. This approach is useful for determining accurate colors of extended sources. Except where noted below, we adopt CModel magnitudes, which use a composite of the best-fit exponential and de Vaucouleurs profiles (Abazajian et al. 2004; Bosch et al. 2018). The median 5σ limiting CModel magnitudes are listed in Table 1. For reference, we also include 5σ limits for PSF magnitudes and for magnitudes measured within 1.5 arcsec apertures. The values in Table 1 are the magnitudes at which 50% of all detected sources have signal-to-noise ratios $S/N \geq 5$. We verified that, for the circular aperture and PSF cases, these values are very similar (within 0.05 mag) to the limits directly measured at randomly placed positions within 40 arcmin of the field center that are free of sources. In all bands the sensitivity declines by 0.2 mag from the center of the field to a radius of 40 arcmin, then deteriorates rapidly at larger radii. The majority of our analysis is therefore confined to the inner 40 arcmin.

2.2. J0148 Lyα Opacity

Before proceeding to the LAE selection, we note that our imaging data allow us to check the Lyα $\tau_{\text{eff}}$ measurement along the J0148 line of sight. Here, we use PSF fluxes, since the object is known to be point-like. We measure a narrowband flux from the quasar of $F_{\lambda}^{\text{NB816}} = (1.9 \pm 1.0) \times 10^{-20}$, erg s$^{-1}$ cm$^{-2}$ Å. We meanwhile measure an $i\lambda$ flux from the quasar of $F_{\lambda}^{\text{i}} = 3.7 \times 10^{-18}$, erg s$^{-1}$ cm$^{-2}$ Å, with negligible error. We use the $i\lambda$ flux to scale the X-Shooter spectrum presented in Becker et al. (2015) by convolving the spectrum with the $i\lambda$ transmission curve, and estimate an unabsorbed continuum flux at the NB816 wavelength of $F_{\lambda}^{\text{cont}} = 2.0 \times 10^{-17}$, erg s$^{-1}$ cm$^{-2}$ Å. These measurements translate into an effective optical depth over the NB816 wavelength range of $\tau_{\text{eff}} = -\ln(F_{\lambda}^{\text{NB816}}/F_{\lambda}^{\text{cont}}) = 6.94^{+0.68}_{-0.40}$ (1σ), with a 2σ lower limit of $\tau_{\text{eff}} \geq 6.26$. These values are consistent with the 2σ limit of $\tau_{\text{eff}} \geq 7.2$ measured by Becker et al. (2015) for the 50 h$^{-1}$ Mpc section centered at $z = 5.796$, which largely overlaps but is ~70% longer than the NB816 passband.

2.3. LAE Selection

Candidate $z = 5.7$ LAEs are selected to have a narrowband excess indicative of Lyα emission and an $r2 - i2$ color consistent with Lyα forest absorption by the IGM. Following Ouchi et al. (2008), we impose the following selection criteria:

\[
i2 - \text{NB816} \geq 1.2, \quad \text{and} \quad \left[ (r2 > 2\sigma_{r2}) \text{ or } (r2 \leq 2\sigma_{r2} \text{ and } r2 - i2 \geq 1.0) \right]. \tag{2}
\]

The narrowband excess is intended to identify line emitters, while the broadband criteria are used to avoid low-redshift interlopers. We note that we do not include an additional bluer filter (e.g., $g$ or $V$), as done by Ouchi et al. (2008, 2018), Shibuya et al. (2018a), and Konno et al. (2018), that would further help to eliminate low-redshift sources. On the other hand, similar to Ouchi et al. (2008), we require all sources detected at more than $2\sigma$ in $r2$ to satisfy our $r2 - i2$ cut. This is somewhat more restrictive than the $3\sigma$ threshold used by Ouchi et al. (2018), Shibuya et al. (2018a), and Konno et al. (2018). These factors may affect the contamination rate from lower-redshift interlopers. As discussed below, however, we do not expect our main findings to be significantly impacted because the contamination should be uniform across our field. Similar to Ono et al. (2018) and Shibuya et al. (2018a) we also select on a number of pipeline flags to avoid blended or contaminated sources. For a list of flags see Shibuya et al. (2018a). Sources are chosen to have $\text{NB816} \leq 26.0$ and $S/N(\text{NB816}) \geq 5$, and to lie within $45\arcmin$ of the quasar position. Each source satisfying these criteria is visually inspected in the combined images. This check is used to reject uncorrected hot pixels and cosmic rays, rapidly moving objects that appear as trails in the combined images, noise features in the outskirts of bright objects, and other artifacts. For candidates passing this initial visual inspection, individual $\text{NB816}$ exposures are examined as a further check for moving or other spurious sources that appear in only one or a small subset of the exposures. In total, 806 LAE candidates pass our selection process. Their properties are summarized in Table 2. Cutout images for four of these objects, spanning a range of $\text{NB816}$ magnitude, are shown in Figure 2.

The goal of this paper is to determine the relative density of LAEs near the quasar line of sight by self-consistently comparing this region to the outskirts of the HSC field. We therefore do not attempt to make a detailed completeness estimate that would be needed to determine a luminosity function. Nevertheless, we can compare our number counts to previous results from the literature. In Figure 3 we plot the surface density of LAE candidates in the J0148 field as a function of $\text{NB816}$ magnitude. Raw results are shown, along with results roughly corrected for completeness, where the completeness within each half magnitude bin is estimated as the fraction of all $\text{NB816}$ sources in that bin that meet our $S/N \geq 5$ cut. For comparison, we plot the surface density of LAEs from the Subaru Suprime-Cam observations of Ouchi et al. (2008), and the shallower Hyper Suprime-Cam observations of Konno et al. (2018; previously described in Shibuya et al. 2018a), both corrected for completeness. Overall we find good agreement with the surface densities of these works, which gives us confidence in our selection process. We note that some level of contamination is expected in our sample. We address this in Section 3.3.

3. Results

3.1. Spatial Distribution of LAE Candidates

The distribution of LAE candidates on the sky is shown in Figure 4. Symbols marking the location of LAE candidates are color-coded according to their $\text{NB816}$ magnitude. The dotted circles centered on the quasar position are drawn in increments of $10$ h$^{-1}$ Mpc projected distance. As noted above, our sensitivity is roughly constant out to $\Delta \alpha \approx 40\arcmin$ ($R \approx 66$ h$^{-1}$ Mpc).

We compute the surface density of LAEs in radial bins centered on the quasar position. We use $10$ h$^{-1}$ Mpc bins in all but the outermost annulus, which is truncated at $45\arcmin$ ($74.5$ h$^{-1}$ Mpc). Raw surface densities are corrected by a factor $\approx \gamma_{\text{NB816}}^R / \gamma_{\text{NB816}}^R$, where $\gamma_{\text{NB816}}^R$ is the number density of all
narrowband sources (not just LAE candidates), with \( NB816 \leq 26 \) and \( S/N \geq 5 \) within a radial bin, and \( \Sigma_{\text{all}}^{\text{NB816}} \) is the number density of narrowband sources meeting these criteria within \( \Delta \theta \leq 40' \). These corrections, which are less than 10%, are meant to account for radial variations in sensitivity, as well as for missing areal coverage due to the presence of bright sources. Our results are summarized in Table 3, and the corrected surface density of LAE candidates is plotted as a function of radius in Figure 5. The dotted line shows the mean “background” surface density computed over \( 15' \leq \Delta \theta \leq 40' \), which is 0.049 (h \(^{-1}\) Mpc \(^{-2}\)). The number density of LAE candidates is consistent with this value in all bins at \( R \geq 20 h^{-1} \text{Mpc} \). Near the quasar position, however, the number density is significantly lower. We find only one candidate within 5 h \(^{-1}\) Mpc (3') of the quasar line of sight, and four within 10 h \(^{-1}\) Mpc (6'), or roughly one-quarter of the background density.

We can assess the significance of the underdensity of LAE candidates around the quasar in two ways. In terms of Poisson statistics, for a background number density of 0.049 (h \(^{-1}\) Mpc \(^{-2}\)), the expected number of detections within 10 (20) h \(^{-1}\) Mpc is 15.3 (61.2), and the probability of detecting 4 (28) or fewer candidates is \( 7 \times 10^{-4} \) (3 \( \times 10^{-5} \)). These values ignore the somewhat higher sensitivity at the center of the field, but they also ignore clustering. For randomly placed circular apertures of radius 10 (20) h \(^{-1}\) Mpc that fall entirely within 40' of the quasar position, the fraction containing at most 4 (32) candidates is 0.037 (0.027). The low density of LAE candidates within 20 h \(^{-1}\) Mpc of the line of sight toward J0148 therefore appears to be highly significant.

To better visualize the spatial distribution of LAE candidates, we create a source density map. To do this, we superimpose a regular grid of 0.4 h \(^{-1}\) Mpc (0.24) pixels onto the map of LAE candidates shown in Figure 4. At each grid point, we find the distance, \( d_{10} \), to the tenth nearest candidate. This distance is converted into a source surface density as \( \Sigma_{\text{LAE}} \propto d_{10}^{-2} \). The \( \Sigma_{\text{LAE}} \) values are normalized by their mean value, and the grid is smoothed using a Gaussian kernel of \( \sigma = 2.0 h^{-1} \text{Mpc} \). Finally, we truncate the map at \( \Delta \theta = 40' \) to exclude regions with lower sensitivity. The result is shown in Figure 6. The quasar line of sight passes near the center of an elongated low-density region that extends roughly 40 h \(^{-1}\) Mpc north–south and 20 h \(^{-1}\) Mpc east–west. This is another indicator that the extreme Gunn-Peterson trough toward J0148 is associated with a region that is highly underdense in LAEs.

### 3.2. Comparison to Models

We now turn to comparing our results to predictions from models for the large spread in IGM Ly\( \alpha \) opacities near \( z \approx 6 \). Here, we consider the UBV fluctuation model of Davies & Furlanetto (2016) and the temperature fluctuation model of D’Aloisio et al. (2015), in which deep Gunn-Peterson troughs such as the one toward J0148 arise in underdense and overdense regions, respectively. In this section, we briefly describe the implementation of these models in Davies et al. (2018) and their predictions for LAEs in the J0148 Gunn-Peterson trough. We also consider a model in which strong UVB fluctuations are driven by rare, bright sources (QSOS), as in Chardin et al. (2015, 2017).
The UVB and temperature fluctuations were computed in a volume 546 h⁻¹ Mpc on a side, using the semi-numerical reionization code 21cmFAST (Mesinger et al. 2011) to compute the density field and dark matter halo distributions (minimum halo mass of 2 × 10⁹ M⊙). For the galaxy UVB model, ionizing luminosities were assigned to dark matter halos via abundance matching to the Bouwens et al. (2015; non-ionizing) UV luminosity function, allowing the ratio of ionizing to non-ionizing luminosities to be a free (but uniform) parameter that is later chosen to produce a predetermined mean H I photoionization rate. The UVB was then computed on a coarse 156° grid with a spatially fluctuating mean free path of ionizing photons following the method of Davies & Furlanetto (2016), assuming an average mean free path of 10.5 h⁻¹ Mpc. As noted above, this is roughly a factor of three smaller than would be expected from a naive extrapolation of lower-redshift values (Worseck et al. 2014), although it is possible that some of the highest-redshift (z ~ 5) direct measurements are biased high (D’Aloisio et al. 2018).

Motivated by the possibility of a QSO-dominated UVB (Giallongo et al. 2015; Chardin et al. 2017, but see McGrer et al. 2018; Parsa et al. 2018), here we extend the modeling framework of Davies et al. (2018) to include a simple QSO model of UVB fluctuations. In this model we abundance-matched dark matter halos to QSOs from the Giallongo et al. (2015) luminosity function and assumed the Lusso et al. (2015) QSO spectrum to compute their ionizing luminosities, with zero contribution to the UVB from galaxies. We note that this is in some sense a more extreme QSO model than the one used by Chardin et al. (2017), who included a minor contribution from galaxies. We choose an average mean free path of 42 h⁻¹ Mpc, which is much longer than the one in our galaxy model, to reproduce the measured UVB strength at z ~ 5.7 (D’Aloisio et al. 2018). As in the galaxy UVB and Chardin et al. (2017) QSO models, the mean free path varies spatially, scaling with the local H I ionization rate, Γ_H I, and the overdensity, Δ = ρ/ρ_c as λ_mfp ∝ Γ_H I Δ⁻¹. Fine lifetime effects may play a large role in the structure of the radiation field (e.g., Croft 2004; Davies et al. 2017), but for computational simplicity and consistency with Chardin et al. (2017), we assumed a static QSO population. Example slices through the galaxy UVB and QSO UVB radiation fields are shown in Figure 7.

To model temperature fluctuations, we used 21cmFAST to compute a reionization redshift field (mean z_reion = 8.8; see Figure 3 in Davies et al. 2018), and then assumed that the gas in each cell is heated to T_reion = 30,000 K at its corresponding reionization redshift. The subsequent thermal evolution of each cell, predominantly cooling via inverse Compton scattering off of CMB photons and through adiabatic expansion, was then integrated from its reionization redshift to z' = 5.7 following a method similar to Upton Sanderbeck et al. (2016). The temperatures are illustrated in Figure 7.

The opacity of the Lyα forest was computed for 1,000,000 50 h⁻¹ Mpc skewers in each model using the fluctuating Gunn-Peterson approximation (Weinberg et al. 1997) with optical depths re-scaled to reproduce the median effective optical depth of the Lyα forest on 50 h⁻¹ Mpc scales at z = 5.7 (τ_eff ~ 3.5). All three models, including our new QSO UVB 21cmFAST model, would presumably further weaken the correlation between density and Lyα opacity seen in Figure 9.

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**Figure 2.** Cutout images for a selection of LAE candidates. Images are 10'' on a side and are centered on the candidate position. From left to right, columns show the r2, i2, and NB816 bands. The NB816 magnitude for each candidate is displayed on the right. These objects were chosen to have S/Ns near the median among objects of similar magnitude.

**Figure 3.** Surface density of LAE candidates as a function of NB816 magnitude. The open squares show our raw results averaged over the entire HSC field. Filled squares have been approximately corrected for completeness. Note that the raw and corrected values are only significantly different in the faintest bin. Error bars for the J0148 field are 68% Poisson intervals. Completeness-corrected values from Ouchi et al. (2008) and Konno et al. (2018) are shown for comparison. Values for the four HSC fields of Konno et al. (2018) are plotted separately, and only include magnitude bins where the completeness correction is moderate (up to ~tens of percent).

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*An alternative would be to randomly assign QSOs to massive halos. This would presumably further weaken the correlation between density and Lyα opacity seen in Figure 9.*
generally reproduce the distribution of observed $\tau_{\text{eff}}$ from Becker et al. (2015) (Figure 8).

To predict the distribution of LAEs in these simulations, we assigned Ly$\alpha$ equivalent widths to galaxies using the probabilistic prescription presented in Dijkstra & Wyithe (2012). Galaxies were assumed to have a fixed UV spectrum $F_\lambda \propto \lambda^{-2}$, a narrow Ly$\alpha$ emission line, and a cutoff at wavelengths shorter than rest-frame Ly$\alpha$ due to the onset of Ly$\alpha$ forest absorption. We then selected LAEs in mock narrowband observations using the same filters and color cuts as Ouchi et al. (2008). We chose a UV spectral index of $\beta = 2$ to be consistent with typical UV-selected galaxies at $z \sim 6$ (Bouwens et al. 2014), but we note that LAEs may have somewhat bluer UV continua ($\beta = -2.9 \pm 1.0$, Ono et al. 2010; $\beta \sim -2.3$, Jiang et al. 2013). Due to the relatively short wavelength coverage of the i2 filter and our EW-based
prescription for the Lyα line strengths, a bluer UV continuum would only change the narrowband excess of our simulated LAEs by a few percent, so we do not expect our predictions to be sensitive to this assumption.

As discussed in Dijkstra & Wyithe (2012), there is a moderate inconsistency in their approach that tends to overproduce the total number of LAEs. To adjust for this, we discard a random $\sim 50\%$ of the selected LAEs, thereby matching the normalization of the Ouchi et al. (2008) LAE luminosity function. Due to the large number of LAEs in the simulation, and the large volume probed by our mock observations, our predictions for the LAE distributions are insensitive to the random seed used to discard potential LAEs.

In Figure 9 we compare the model predictions for the radial distribution of LAEs in fields with $\tau_{\text{eff}} > 7$ to our observations of the J0148 field. Surface densities as a fraction of the mean are shown in order to minimize the impact of observational incompleteness and uncertainties in the model normalizations. Overall, we find excellent agreement with the predictions of the galaxy UVB model, with the observations closely following the expected decrease in surface density close to the QSO line of sight. Such a strong decrease is not generally expected for the QSO model, in which UVB and density fluctuations are less tightly coupled; however, our innermost data point still falls within the 95% expected bounds. In contrast, the temperature model appears strongly disfavored. Whereas an upturn in galaxy density is expected near the quasar line of sight, the opposite trend is observed.

### 3.3. Caveats

At face value, the results presented here support a picture wherein high IGM Lyα opacity near $z \sim 6$ occurs in low-density regions. As discussed above, this is consistent with a model wherein large-scale opacity fluctuations are created by spatial variations in the UVB, and disfavors a scenario wherein the opacity fluctuations are due mainly to temperature variations. While this conclusion may seem straightforward, however, it is worth considering a few caveats.

Our basic observational result is that the projected surface density of LAE candidates around the quasar line of sight is significantly lower than the “background” density at larger radii. This is a self-consistent comparison and should be robust to incompleteness, provided that our selection efficiency for LAE candidates is roughly constant across the field. Given that the correction factors listed in Table 3 are close to unity at all radii, this is probably close to the truth. As in all narrowband surveys for high-redshift LAEs, our sample will be contaminated at some level by low-redshift interlopers and other spurious sources. Shibuya et al. (2018b) estimated a low ($\sim 8\%$) contamination rate based on spectroscopic follow-up of $z = 5.7$ LAE candidates selected using criteria similar to those used here, although the spectroscopically confirmed sources are all brighter than $NB816 = 25.3, 0.7$ mag brighter than our faintest sources. As long as contaminants do not dominate our sample (which seems unlikely, given our broad agreement with the Ouchi et al. (2008) number densities), contamination should not significantly affect our fundamental result. If the contaminants are distributed randomly in the field, then removing the contaminants would tend to decrease the surface density of sources by the largest fraction in regions where the total source density is low. This would tend to enhance the deficit of LAEs around J0148. The contaminants are unlikely to trace the spatial distribution of genuine LAEs. Nevertheless, we can evaluate the potential impact of contaminants in this case. In
trials where we randomly reject 30% of all sources as interlopers, the fraction of randomly placed 20 h^{-1} Mpc radius apertures that contain a number of enclosed sources less than or equal to the number of sources within 20 h^{-1} Mpc of the quasar position is ≤7% in 95% of trials. The deficit of LAE candidates around the quasar is therefore likely to be robust to high levels of contamination, even in this unphysical scenario.

A second possible concern is how accurately LAEs trace the underlying density field on these scales. In imaging of two high-redshift quasar fields, Díaz et al. (2014) found that the spatial distribution of narrowband-selected LAEs at z = 5.7 is not well matched by the distribution of broadband-selected Lyman Break Galaxy (LBG) candidates chosen to lie near z ~ 5.7. Ota et al. (2018) found a similar result for LAEs at
Without the spectroscopic redshifts of the broadband-selected objects, however, it is difficult to know how closely these populations overlap in redshift space. Our baseline assumption is that galaxies that intrinsically emit Ly\(\alpha\) radiation trace the underlying density field on large (\(\gtrsim\)Mpc) scales. This should be true even if LAEs typically reside in lower-mass halos than UV-selected LBGs at the same redshift (e.g., Ouchi et al. 2010; Bielby et al. 2016).

Perhaps a more serious concern is whether Ly\(\alpha\) emission from galaxies could be suppressed in the vicinity of a deep Gunn-Peterson trough. After all, we selected this region because it exhibited very strong Ly\(\alpha\) absorption along the quasar line of sight. It is therefore worth asking whether galaxy Ly\(\alpha\) emission could also be strongly extinguished. There is strong evidence that the fraction of star-forming galaxies with detectable Ly\(\alpha\) emission declines at \(z > 6\) (Fontana et al. 2010; Treu et al. 2013; Pentericci et al. 2014; Schenker et al. 2014; Tilvi et al. 2014). This decline is typically attributed to scattering by neutral gas along the line of sight, an indication of ongoing reionization (e.g., Bolton & Haehnelt 2013; Mesinger et al. 2015; Mason et al. 2018). In principle there could be remaining patches of neutral gas near \(z \sim 5.7\) along the J0148 line of sight. We note, however, that the quasar spectrum shows transmission in the Ly\(\beta\) forest, which requires a highly ionized IGM, near the central redshift of the \(NB816\) filter (Figure 1). An explanation for the lack of LAEs in this region that appeals to neutral gas in the IGM would also need to explain this transmission.

Alternatively, a locally low UVB could enhance the apparent deficit of sources by making LAEs more difficult to detect. If the UVB is highly suppressed, then dense circumgalactic gas may become increasingly neutral. This would tend to scatter Ly\(\alpha\) out to larger galactic radii, decreasing its surface brightness (e.g., Sadoun et al. 2017; Weinberger et al. 2018). In this scenario, the striking deficit of LAEs around the J0148 line of sight could be due to a lower-than-average number density of galaxies combined with Ly\(\alpha\) suppression. In principle, we can test this possibility by conducting a separate survey for continuum-selected galaxies. Such a search would need to be deep enough to detect a sufficient number of sources to probe the density field, and would need photometric redshifts (or spectroscopic redshifts from lines other than Ly\(\alpha\)) that were sufficiently accurate to identify galaxies within the redshift range of the \(NB816\) filter and/or the full J0148 absorption trough. As shown by Davies et al. (2018), the ability to probe the entire length of the trough means that a survey for continuum-selected galaxies could provide an even stronger test of the \(\tau_{\text{eff}}\) fluctuation models than the LAE results presented here.

4. Summary

We have conducted a search for LAEs at \(z = 5.7\) in the field of the \(z = 6.0\) quasar ULAS J0148+0600, whose spectrum contains an exceptionally long (110 h\(^{-1}\) Mpc) and opaque (\(\tau_{\text{eff}} > 7\)) Ly\(\alpha\) absorption trough. These observations are designed to test competing models for the origin of IGM Ly\(\alpha\) opacity fluctuations at \(z \sim 6\) (Fan et al. 2006; Becker et al. 2015; Bosman et al. 2018). If the fluctuations are due to spatial variations in an ionizing UV background dominated by galaxies, then the J0148 trough should arise in a low-density region (Davies & Furlanetto 2016). For fluctuations in a QSO-dominated UVB (Chardin et al. 2017), high-opacity regions can have a wide range of densities, provided the local UVB is low. If temperature fluctuations are responsible, then such troughs should trace high-density regions (D’Aloisio et al. 2015).

In 1.8 square degrees of Subaru Hyper Suprime-Cam imaging we identify 806 LAE candidates down to \(NB816 = 26.0\) via their narrowband excess. The spatial distribution of these galaxies shows a clear deficit within \(\sim 20 h^{-1}\) Mpc projected distance of the quasar line of sight. This result comes from a self-consistent comparison of the projected number density of galaxies across the HSC field, and should be minimally sensitive to completeness. Contamination of our sample by lower-redshift and spurious sources is also unlikely to create such a large absence at the center of the field. We are therefore confident that there is a genuine scarcity of LAEs near the quasar position.

The dearth of LAE candidates near the quasar line of sight is consistent, at face value, with models wherein the observed scatter in IGM Ly\(\alpha\) opacity near \(z \sim 6\) is driven by spatial fluctuations in the UVB, and disfavors a model based on temperature variations. The radial distribution of LAEs follows the expected profile for a galaxy-dominated UVB, although it is also within the broad distribution of profiles expected for a QSO UVB. LAE surveys in additional fields surrounding deep troughs may help to determine whether a galaxy or QSO UVB is preferred.

In the galaxy UVB model, the J0148 trough arises from a void where the ionizing radiation field is suppressed, increasing the hydrogen neutral fraction and therefore the Ly\(\alpha\) opacity. The association of a high-opacity line of sight with a low-density region would be the opposite of what is expected at lower redshifts, where the hydrogen ionizing background is suppressed, increasing the density of galaxies combined with Ly\(\alpha\) suppression. In principle, we can test this possibility by conducting a separate survey for continuum-selected galaxies. Such a search would need to be deep enough to detect a sufficient number of sources to probe the density field, and would need photometric redshifts (or spectroscopic redshifts from lines other than Ly\(\alpha\)) that were sufficiently accurate to identify galaxies within the redshift range of the \(NB816\) filter and/or the full J0148 absorption trough. As shown by Davies et al. (2018), the ability to probe the entire length of the trough means that a survey for continuum-selected galaxies could provide an even stronger test of the \(\tau_{\text{eff}}\) fluctuation models than the LAE results presented here.
believed to be roughly uniform on large scales. For example, regions of exceptionally strong Lyα forest absorption at \( z \sim 2-3 \) have been observationally associated with large-scale galaxy overdensities (e.g., Cai et al. 2016; Lee et al. 2016).

If UVB fluctuations are indeed present it could have significant implications for reionization. As noted by D’Aloisio et al. (2018), in order to explain the full distribution of IGM Lyα opacities within the fluctuating UVB model, a short and spatially varying mean free path must be coupled with a mean ionizing emissivity that is a factor of \( \sim 2 \) higher than what has been previously inferred at these redshifts. It is unclear whether a higher emissivity tempered by a shorter mean free path would necessarily produce a more rapid reionization, but these factors are clearly important for reionization models. More generally, any successful reionization model would have to predict large-scale UVB fluctuations at \( z \lesssim 6 \).

We have assumed that LAEs are reliable tracers of the density field on large scales. It is important to consider, however, whether galaxy Lyα emission could be scattered in regions of extreme IGM Lyα opacity. A survey in the same region for continuum-selected galaxies would help to determine whether there are relatively few LAEs near the J0148 line of sight because this is a genuinely low-density region or because galaxy Lyα emission in this region is suppressed. Lyα scattering would need to decrease the number density of observable LAEs by a factor of \( \sim 2-3 \) in order to fully explain the deficit around the J0148 line of sight. Both density and scattering effects may be important, however.

Finally, we note that this is only a single line of sight, and we have probed only the high-opacity end of the \( \tau_{\text{eff}} \) distribution. Observations of additional fields spanning a range in line-of-sight Lyα opacity would help to clarify which, if any, of the models considered here are correct.

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