HOW UNIVERSAL IS THE GUNN-PETERSON TROUGH AT $z \sim 6$?
A CLOSER LOOK AT THE QUasar SDSS J1148+5251

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Abstract

Detectable flux is visible in the Ly$\alpha$ and Ly$\beta$ troughs of the highest redshift ($z = 6.42$) quasar found to date, SDSS J1148+5251. This has previously been interpreted as continuum contamination from an interloper galaxy at $z = 4.94$. We examine the Ly$\gamma$ trough of SDSS J1148+5251 and show that this interpretation is untenable: the spectrum does not show the continuum break in a $z = 4.94$ galaxy expected from absorption by the intervening Ly$\alpha$ forest. Therefore, flux must be leaking through at least one of the troughs from the quasar itself. Contrary to previous claims, the flux ratios in the Ly$\alpha$ and Ly$\beta$ troughs are consistent with pure transmission. From the Ly$\gamma$ trough, we place an upper bound on the effective Ly$\alpha$ optical depth at $z \sim 6.2$ of $\tau_{\text{eff}} < 15.4$ ($\sigma$). This implies a highly ionized intergalactic medium along this line of sight and significant cosmic variance in the transition toward complete Gunn-Peterson absorption.

Subject headings: cosmology: theory — early universe — galaxies: formation — galaxies: high-redshift — quasars: absorption lines

Online material: color figure

1. INTRODUCTION

Despite spectacular progress in recent years, the reionization history of the universe remains shrouded in mystery. A crucial missing piece of the puzzle is the precise ionization state of the intergalactic medium (IGM) at $z = 6$. The large optical depth of the IGM to hydrogen Lyman transitions implies that Gunn & Peterson (1965) absorption can (at best) constrain the volume- and mass-weighted neutral fractions to be $x_{\text{H},V} \lesssim 10^{-3}$ and $x_{\text{H},M} \lesssim 10^{-2}$, respectively (Fan et al. 2002). It is plausible that the IGM is still highly ionized at $z = 6$, with full reionization occurring much earlier. On the other hand, modeling of the spectral regions around two quasars at $z \approx 6.2$ may indicate larger neutral fractions ($x_{\text{H}} \approx 0.2$; Wyithe & Loeb 2004a; Mesinger & Haiman 2004). At stake is the very nature of reionization: if these claims are correct, then reionization must be an extremely rapid process, since the IGM is known to be highly ionized ($x_{\text{H}} \lesssim 10^{-3}$) by $z = 5.9$ along all observed lines of sight (Fan et al. 2003).

It is thus worth considering the IGM absorption in more detail. In particular, a completely dark Gunn-Peterson trough at $z \sim 6$ is not necessarily universal. Both the Ly$\alpha$ and Ly$\beta$ troughs of the highest redshift quasar found to date, SDSS J1148+5251, contain detectable flux (White et al. 2003). In this Letter, we show that its previous interpretation as continuum contamination from an interloper galaxy at $z = 4.94$ is inconsistent with the observed flux ratios blueward and redward of the expected continuum break owing to Ly$\alpha$ forest absorption. Therefore, some of the flux is true transmission through holes in the high-redshift Ly$\alpha$ forest. We derive our strongest constraints from the Ly$\gamma$ trough, which was ignored in previous analyses and is uncontaminated by flux from an interloper. The presence of flux implies either that the IGM is highly ionized at $z \geq 6$ or that there is significant cosmic variance along different lines of sight.

2. THE LY$\gamma$ TROUGH IN SDSS J1148+5251

Detectable flux and a network of transmission features are seen in both the Ly$\alpha$ and Ly$\beta$ troughs of SDSS J1148+5251. White et al. (2003) interpreted this to be continuum contamination from interloper galaxies at $z = 4.94$ for two reasons: (1) Strong C IV absorption features appear at $z = 4.9$, so the apparent strong Ly$\beta$ spikes at $z = 6.02$, 6.06 could be Ly$\alpha$ emission from $z \approx 4.94$. (2) The flux ratios of the troughs appear inconsistent: there is too little light in the Ly$\beta$ trough given the Ly$\alpha$ transmission. We argue instead that this interpretation is untenable and that the flux in both the Ly$\beta$ and Ly$\gamma$ troughs represent genuine transmission. Note that if residual flux in any of the Ly$\alpha$, $\beta$, and $\gamma$ troughs can be attributed to the quasar rather than an interloper, the IGM must still be highly ionized along this line of sight.

First, consider the Ly$\beta$ trough at $z_\beta \sim 5.95$–6.1, which has a plethora of emission spikes. Can these be Ly$\alpha$ emission lines from a $z \sim 5$ protocluster? They end abruptly at $z_\beta = 5.95$: the residual flux changes from $F_{\text{Ly}\beta}(z_\beta) = 6.33$–6.40) = 29.0 ± 1.5 to $F_{\text{Ly}\beta}(z_\beta = 6.25$–6.32) = 4.3 ± 1.4, where $F_{\text{Ly}\beta}$ is the flux $F$ in units of $10^{-20}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$. The wavelength of Ly$\beta$ at $z_\beta = 5.95$ corresponds to Ly$\gamma$ at $z_\gamma = 6.33$, precisely the boundary of the quasar proximity zone seen in Ly$\alpha$ and Ly$\beta$. This strongly suggests that the flux seen at the lower redshift end of the Ly$\beta$ forest represents true transmission. Barring an astonishing coincidence, flux from a $z \sim 5$ interloper would not exhibit a discontinuity precisely at the edge of the (higher redshift) quasar proximity zone. Thus, the Ly$\beta$ trough is already highly transparent at these redshifts, and there is strong circumstantial evidence that some of the approximately five strong emission features with $z_\beta \sim 5.95$–6.1 are real (cf. the completely opaque SDSS J1030+0524; White et al. 2003).

Now consider the detectable flux in the Ly$\gamma$ trough (specifically, the stretch $z = 6.17$–6.32, which lies outside the quasar’s apparent region of influence and ends where the Ly$\gamma$ trough becomes contaminated by Ly$\delta$ at $\lambda = 6962$ Å, corresponding...
to $z_p = 6.16$, White et al. (2003) suggest that the corresponding Lyα and Lyβ troughs are contaminated by continuum emission from the interloper galaxy so that detected flux is not significant. To be conservative, let us ignore the transmitted flux in the Lyβ trough, which is potentially also contaminated by emission-line features from the $z \approx 5$ protocluster. We find that $F_{-20}(\text{Lyα}) = 3.0 \pm 0.9$, while $F_{-20}(\text{Lyγ}) = 4.9 \pm 0.9$; these regions correspond to $\lambda = 1467–1498$ Å and $\lambda = 1174–1199$ Å in the rest frame of an interloper galaxy at $z = 4.94$. These flux ratios are strongly inconsistent with the expected continuum of a $z \approx 5$ galaxy, which should have a strong break due to the intervening Lyα forest. Songaila & Cowie (2002) obtain a flux suppression factor $T_{i} = 0.14 \pm 0.03$ for the Lyα forest in this redshift interval (Becker et al. 2001 find $T_{i} = 0.11$). Even if the flux in the Lyα trough is entirely due to continuum contamination from the interloper, the implied contribution to the Lyγ trough is well within the noise: $F_{-20}(\text{Lyγ}) = 0.4(T_{i}/0.14) \ll F_{-20}(\text{Lyα})$. Almost all the observed flux in the Lyγ trough must therefore be genuine transmitted flux from the quasar. Thus, the Lyγ trough places the strongest constraint on the IGM ionization state along this line of sight.

In principle, a galaxy associated with the C IV absorbers at $z = 4.90$ could ionize the IGM at $z = 5$, creating a transparent Lyα window there. Indeed, this is probably the origin of the strongest emission peak in the Lyβ trough at $\lambda = 7205$ Å ($z_p = 6.02$; White et al. 2004). However, the proximity zone of this galaxy is too small to account for other transmission features seen in the Lyβ trough, which would require ionizing the IGM on comoving scales of order $L \approx 150(\Delta z/0.3)$ Mpc. Lyman break galaxies at $z \approx 3–4$ show excess Lyα transmission on scales $L \approx 0.5$ Mpc comoving (Adelberger et al. 2003). It is unlikely a $z = 5$ galaxy could affect a significantly larger volume.

3. IMPLICATIONS FOR THE IGM AT $z = 6$

Having established the reality of residual flux from SDSS J1148+5251, we will now consider its implications for reionization at $z \approx 6$. We must first estimate the effective optical depths $\tau_{\text{eff}}$ in each transition. We begin by summarizing our methodology and the error budget. The errors for Lyγ transmission $T_{i} = T_{\text{obs}}/T_{i} T_{0}$ must include not only pixel noise but also the cosmic variance in foreground transmission in Lyα and Lyβ. Previous analyses have often neglected this additional scatter. It has been measured in quasar samples; we use the values in Table 2 of Songaila & Cowie (2002), who tabulate the measured ($T_{i}'$), $\sigma_{T_{i}}$ for six redshift bins between $z = 4.1$ and 5.5. However, they use fixed wavelength intervals, and $\sigma_{T_{i}}$ obviously depends on the corresponding comoving length $L$. Poisson statistics are inappropriate because long-wavelength modes could dominate the variance. To estimate $\sigma_{T_{i}}$, we follow Lizd et al. (2002), who argue that the transmission power spectrum takes the shape (although not the normalization) of the linear mass power spectrum on large scales, yielding

$$\sigma_{T_{i}}^{2} = 2 \int_{0}^{\infty} \frac{dk}{2\pi} \frac{\sin{(kL/2)}}{kL} P(k) + \frac{\sigma_{n}^{2}}{N},$$

where $\sigma_{n}$ is the noise per pixel, $N$ is the number of pixels, and $P(k) = B \exp\left\{-ak^{2}\right\}/(dk/2\pi)$,$bP_{\text{mass}}(k)$, where $a \approx k_{\text{J}}^{-1/2}$, $k_{\text{J}}$ is the Jeans wavenumber, and $B$ is normalized to the observed $T_{i}$ for some observed stretch. The first term in equation (1) typically dominates by an order of magnitude. For the large length scales of interest, $P(k)$ is fairly flat, and $\sigma_{T_{i}} \propto L^{-1}$, as expected for a white noise power spectrum. This $A \text{nsat}$ assumes a homogeneous ionizing background $G$; if $G$ exhibits small-scale fluctuations, $\sigma_{T_{i}}$ could be larger. Note that there is no cosmic variance in $T_{i}$, because we have observed the corresponding Lyα transmission (at $z_{a} = 5.9$) along the same line of sight.

Another crucial item is uncertainty in the quasar continuum, particularly because the Lyα line is much broader than the Lyβ and Lyγ lines and generally spills over into the observed trough. Uncertainty in the strength of the line creates significant uncertainty in the inferred $\tau_{a}$. To quantify this, we follow White et al. (2003) by comparing the optical depths inferred assuming the composite spectrum from the Large Bright Quasar Survey (LBQS; Brotherton et al. 2001), which includes emission lines, and the pure power-law spectrum of Telfer et al. (2002). The difference between the two captures the uncertainty in emission-line contribution. We normalize the continuum to the observed flux at ~1290 Å.

Table 1 lists the measured effective line optical depths $\tau_{\text{eff}} = \tau_{\text{eff}}$ (Lyγ). The results for Lyα and Lyβ are comparable to those of White et al. (2003). They argued that the pair are incompatible with each other because $\tau_{a} \propto \lambda_{a} f_{\text{a}}$ (where $f_{\text{a}}$ is the oscillator strength of line $\text{a}$), implying $\tau_{a}/\tau_{b} = 6.24$ and $\tau_{a}/\tau_{\text{eff}} = 17.93$. However, these relations are only true at fixed density and only apply to a homogeneous IGM. For the large comoving lengths we consider, the transmission comes from a variety of densities:

$$\langle T_{i} \rangle = \langle \exp \{-\tau_{\text{eff}}(\Delta)\} \rangle = \int \exp \{-\tau(\Delta)\} P(\Delta) d\Delta,$$

where $P(\Delta)$ is the probability distribution of overdensities $\Delta \equiv \rho/\rho_{c}$, $\tau \propto \lambda f_{\text{a}} (1 + z)^{3}\Delta \alpha(T) / \Gamma$ (e.g., Hui & Gnedin 1997), and $\alpha(T)$ is the ionization coefficient. We use the $P(\Delta)$ given by Miralda-Escudé et al. (2000), which is a good fit to numerical simulations. If we assume an equation of state

| Trough | Flux$^a$ | Continuum$^b$ | Total Optical Depth | Line Optical Depth$^c$ | $\tau_{a} (\beta = 2)^d$ | $\tau_{a} (\beta = 3)^d$ |
|--------|--------|-------------|---------------------|------------------------|------------------------|------------------------|
| Lyα    | 3.0 ± 0.9 | (2560, 1730, 1690) | (6.8, 6.4, 6.4) ± 0.3 | (6.8, 6.4, 6.4) ± 0.3 | (6.8, 6.4, 6.4) ± 0.3 | (6.8, 6.4, 6.4) ± 0.3 |
| Lyβ    | 9.0 ± 1.1 | (2140, 1870, 1710) | (5.5, 5.3, 5.2) ± 0.1 | (3.1, 3.0, 2.9) ± 0.1 | (8.2, 7.8, 7.6) ± 0.9 | (6.7, 6.4, 6.2) ± 0.7 |
| Lyγ    | 4.9 ± 0.9 | (2070, 1910, 1710) | (6.1, 6.0, 5.9) ± 0.2 | (2.5, 2.4, 2.3) ± 0.4 | (11.5, 11.2, 10.7) ± 2.1 | (8.4, 8.2, 7.8) ± 1.5 |

$^a$ In units of $10^{-20}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$.

$^b$ Derived from the LBQS composite spectrum and the Telfer et al. (2002) spectral indices for radio-quiet ($\alpha_{\text{L}} = -1.57$) and radio-loud ($\alpha_{\text{L}} = -1.96$) quasars, respectively. Subsequent triplets for the calculated optical depths reflect this ordering.

$^c$ After subtracting off the contribution from foreground absorption. For the Lyβ trough: $\tau_{a} = \tau_{a}(z = 5.1) = 2.38 \pm 0.32$; for the Lyγ trough: $\tau_{a} = \tau_{a}(z = 5.9) = 1.95 \pm 0.25$; the uncertainty in $\tau_{a}(z = 5.9)$ is due to uncertain conversion from $T_{a}(z = 5.9)$ (estimated by comparing the $\beta = 2$ and $\beta = 3$ values).

$^d$ The effective equivalent Lyα optical depth inferred from the nonlinear conversion described in the text, assuming $\tau(\Delta) \propto \Delta^{2}$.
$T \propto \Delta^\gamma$ (where $\gamma \sim 0$–1) and a fluctuating radiation field whose amplitude may be density-dependent, $\Gamma = \Gamma_i \Delta^\gamma$, then $\tau_i = A(z)(1 + z)^{-\beta \Delta^\gamma}$, where $\beta = 2 - 0.7\gamma - \xi$. We can solve for the normalization constant $A(z)$ by demanding $(T_i(A) = T_{\text{obs}}(z))$. Note that $A(z) \propto f_T \lambda / T_i$.

The integral in equation (2) is (Songaila \& Cowie 2002; Songaila 2004):

$$\tau_{\text{eff}} = -A^{(1+3/2\gamma)} + \frac{0.83}{(\beta + 4/3)} \ln A + \text{const.} \quad (3)$$

The leading term implies that $\tau_{\text{eff}} \propto A^{1.4}$ for $\beta = 2$ (corresponding to a uniform radiation field and an isothermal equation of state). Thus, in an inhomogeneous universe the optical depth increases more slowly than linearly as $f_i$ increases or $\Gamma$ decreases. This is because transmission is dominated by rare voids, and the primary effect of decreasing $f_i$ is to increase the range of densities sampled by the line. Evaluating equation (2) numerically with $\Gamma = 0.05$ at $z = 6.15$ (yielding $\tau_e = 7$), we find $(\tau_e/\tau_g, \tau_e/\tau_i) = (2.7, 4.9)$, with weak dependence on redshift, the equation of state, and $\Gamma$. This behavior becomes even more marked if $\Gamma$ is not uniform, which is certainly the case before reionization is complete. For example, if we fix $\tau_e$ but suppose that $\beta > 2$, the optical depth increases even more slowly with $f_i$: for $\beta = 3$, $(\tau_e/\tau_g, \tau_e/\tau_i) = (2.1, 3.4)$. (This could, for example, mimic self-shielding in overdense regions.) Only if the optical depth is independent of overdensity ($\beta = 0$) will we recover the linear scaling. Fluctuations in the radiation field that are uncorrelated with density (so that $\tau \propto \Delta^3$) will produce similar effects. For example, a radiation field with a lognormal probability distribution ($\Gamma$, $\sigma_{\ln \Gamma}$) = (0.02, 1) yields $(\tau_e/\tau_g, \tau_e/\tau_i) = (1.9, 2.9)$.

Thus, the fluctuating density and radiation fields introduce considerable uncertainty in the relations between $\tau_e$, $\tau_g$, and $\tau_i$. As a result, estimating the volume- and mass-weighted neutral fractions $x_{H_1, v}$ and $x_{H_1, M}$ in the IGM from $\tau_{\text{eff}}$ is fraught with uncertainty. We can infer $\langle x_{H_1, v} \rangle \propto \langle \epsilon \rangle$ from $\langle \epsilon^\gamma \rangle$ only in the limit where $\tau \ll 1$ and $\langle \epsilon^\gamma \rangle \approx 1 - \langle \epsilon \rangle$; otherwise, our ignorance of $P(\tau)$ means that a wide variety of $\langle x_{H_1, v} \rangle$ would be consistent with a given observed $\langle \epsilon^\gamma \rangle$. As an illustration, Figure 1 shows the logarithmic integrand $y \Delta P(\Delta) \propto \langle \psi \rangle$ for various quantities $\psi$; all the curves have been normalized to have unit area. Since $\langle \epsilon^\gamma \rangle$ is heavily weighted toward voids and $\langle x_{H_1, v} \rangle$ is weighted toward overdense regions, estimating one from the other is model-dependent. While $x_{H_1, v}$ still shows reasonable overlap with $\langle \epsilon^\gamma \rangle$ (particularly Ly$\beta$ and Ly$\gamma$), $x_{H_1, M}$ is heavily weighted toward large overdensities, and the quasar spectra leave the neutral fraction in such regions essentially unconstrained. Fortunately, reionization is generally characterized by a jump in the photon mean free path and $H$ II filling factor, which are directly related to $x_{H_1, v}$ rather than $x_{H_1, M}$.

With these caveats, we list $\tau_e$ derived from each of the three transitions in the rightmost columns of Table 1 for $\beta = 2, 3$. Within the $2\sigma$ uncertainties, the flux ratios in all three troughs are consistent with flux transmission from the quasar (without an interloper). The apparent inconsistency in White et al. (2003) occurred because they did not integrate over the IGM density distribution. Again, we caution that the conversion between different transitions has large uncertainties (not reflected in the error bars) due to the unknown $P(\tau)$. The true effective optical depth inferred from the Ly$\alpha$ and Ly$\beta$ troughs could also be somewhat higher if there is some continuum contribution from an interloper, which we cannot completely rule out. The most stringent optical depth constraint therefore comes from the Ly$\gamma$ trough, which implies $\tau_e < 15.4$ (2 $\sigma$), with a most likely value $\tau_e \approx 7$–11. By contrast, in SDSS J1030+0524, the 1 $\sigma$ lower limit to the optical depth in the Ly$\beta$ trough is $\tau_{\text{eff}} > 11.1$ (9.9), the Ly$\gamma$ trough yields similar constraints. The uncertainty in Ly$\gamma$ estimates is dominated by unknown foreground absorption; our estimate of $\tau_{\text{eff}} = 3.5 \pm 0.4$ is consistent with the measured value of $\tau = 3.23 \pm 0.04$ at the same wavelengths in SDSS J1030+0524 (where Ly$\gamma$ absorption is negligible, since it lies within the proximity zone of the quasar).

The Ly$\gamma$ trough contains a number of interesting features. There are significant fluctuations within our redshift window; much of the light in the Ly$\beta$ and Ly$\gamma$ troughs comes from a set of narrow spikes at $z = 6.18$. There is also a Ly$\gamma$ counterpart to the strong Ly$\beta$ line at $7205 \AA$ ($\tau_\text{eff} = 6.02$). The redshift alignment of these spikes strongly argues for true IGM transmission. Like the emission feature at $z = 6.08$, these holes are probably due to fluctuations in $\Gamma$ and deserve more detailed study. Note, however, that the IGM never becomes completely optically thick. In the darkest stretch from $z = 6.25$ to 6.32, the spectrum appears completely black in Ly$\alpha$ and Ly$\beta$, but there is an $\sim 3$ $\sigma$ detection of flux in Ly$\gamma$, suggesting that $10 \leq \tau_e \leq 20$. At least along this line of sight, the forest seems to thicken steadily rather than evolve sharply, in contrast to SDSS J1030+0524 (White et al. 2003).

4. Discussion

In this Letter, we have argued that the residual flux in the Ly$\alpha$, Ly$\beta$, and Ly$\gamma$ troughs of SDSS J1148+5251 is not due to an interloper galaxy but represents true transmission in the $z \approx 6$ IGM. This places an upper bound on the effective Ly$\alpha$ optical depth of $\tau_{\text{eff}} \leq 15.4$ (2 $\sigma$), implying that the IGM is still highly ionized at $z \approx 6.3$. It has been argued that the size of the H II regions of the two highest redshift quasars $R_{H_\text{II}} \approx 4.5$ Mpc implies $x_{H_1} > 0.1$ in this range (Wyithe \& Loeb 2004a):

![Image](https://example.com/fig1.png)

**Figure 1.** Logarithmic integrand $y \Delta P(\Delta) \propto \langle \psi \rangle$ as a function of $\Delta$ for $(T_g, T_i, \epsilon_{\text{in}}, \epsilon_{\text{out}})$ and $(\epsilon_{\text{in}}, \epsilon_{\text{out}})$. We assume a uniform ionizing background $\Gamma = 0.04$ at $z = 6.15$ and an isothermal equation of state. The integral for $\langle \epsilon_{\text{in}}, \epsilon_{\text{out}} \rangle$ peaks at high overdensities to the right of the plot. Estimating the neutral fraction from quasar spectra is therefore quite uncertain. [See the electronic edition of the Journal for a color version of this figure.]
\( R_{\text{Hi}} \approx 7 x_{\text{Hi}}^{-1/3} (t_{\text{age}} / 10^7 \text{ yr})^{1/3} \) Mpc, where \( t_{\text{age}} \) is the lifetime of the quasar (note that this also depends on the quasar spectrum and ionizing luminosity). For our purposes, we note that \( R_{\text{Hi}} \) is determined by the mass-weighted neutral fraction \( x_{\text{Hi,M}} \). As we showed in § 3, this is poorly constrained by \( t_{\text{age}} \), because voids containing only a small fraction of the mass dominate the transmission. For instance, if \( x_{\text{Hi,M}} \sim 0.1 \) of the baryons are in neutral self-shielded halos, we could still have \( x_{\text{Hi,V}} \sim x_{\text{Hi,M}} / 6 \sim 0.1 / 200 \sim 5 \times 10^{-4} \), which could easily be accommodated by our results.

A second argument in favor of \( x_{\text{Hi}} \approx 0.1 \) is an indirect detection of the Gunn-Peterson damping wing (Mesinger & Haiman 2004). There is a stretch at the boundary of the \( \text{H} \) ii region of SDSS J1030+0524 with \( \text{Ly} \beta \) but no \( \text{Ly} \alpha \) transmission, implying \( 6 < \tau_{\text{eff}} < 11 \). The absence of any \( \text{Ly} \alpha \) transmission from low-density voids implies a source of smooth opacity, attributed to a strong \( \text{Ly} \alpha \) damping wing with \( \tau > 10^3 \). However, SDSS J1148+5251 contains no such transition region. We also caution that the statistical significance of such transition regions is still unclear. For instance, in SDSS J1148+5251 there is a stretch from \( z = 5.95 \) to 6.0 with \( \text{Ly} \beta \) transmission \( (F_{\text{20}} = 37.9 \pm 1.7) \) but no significant \( \text{Ly} \alpha \) flux \( (F_{\text{20}} = 2.5 \pm 1.7) \). Again, the optical depth ratios are consistent with pure flux transmission \( (\tau_{\alpha} = 6.6 \pm 0.7, \tau_{\beta} = 2.0 \pm 0.4 \Rightarrow \tau_{\alpha,\alpha} \approx 5.5 \pm 1.2) \). This stretch is \( \sim 2.5 \) times longer than the \( \Delta z \approx 0.02 \) zone seen in SDSS J1030+0524, and we have argued that the IGM is highly ionized along this stretch. Such regions therefore need not indicate the presence of a damping wing. More detailed analysis would help shed light on this issue.

Nonetheless, if the region around SDSS J1030+0524 is significantly neutral, this may be a hint of large cosmic variance in the epoch of reionization. Indeed, a strongly fluctuating \( \tau_{\text{eff}} \) is itself a signature of the preoverlap era. In the extreme interpretation that the \( \text{Ly} \alpha \) and \( \text{Ly} \beta \) troughs of SDSS J1030+0524 require \( x_{\text{Hi}} \sim 0.2 \) down to \( z = 5.95 \), this implies a large modulation in the ionization fraction and typical bubble sizes of order \( \Delta z = 0.38 \), or \( L \sim 150 \) Mpc comoving. This is substantially larger than the \( \text{H} \) ii regions of these extremely bright and rare quasars, \( R_{\text{Hi}} \sim 30 \) Mpc comoving. It is also larger than theoretical expectations for the scale of typical \( \text{H} \) ii regions at the tail end of reionization (Furlanetto et al. 2004; Wyithe & Loeb 2004b), so we consider such a scenario to be extremely unlikely. At the other extreme, the measured \( \tau_{\text{eff}} \) are compatible with a slightly faster increase in \( \tau_{\text{eff}} \) along the sight line to SDSS J1030+0524 \( (\tau_{\text{eff}} > 9.9, 2 \sigma) \), than to SDSS J1148+5251 \( (\tau_{\text{eff}} \approx 7-11) \). Whether a highly ionized universe can tolerate such scatter is unclear. Better constraints may come from analyzing the large optical depth fluctuations seen in SDSS J1148+5251. For example, we might expect the \( \text{Ly} \beta \) and \( \text{Ly} \gamma \) troughs in SDSS J1030+0524 to break up into transmission spikes when observed at very high resolution. We have shown that a simple \( \tau_{\text{eff}} \) analysis is a blunt instrument, and strong constraints on reionization require a more sophisticated interpretation.

Note that surveys of \( \text{Ly} \alpha \) emitters have found no evolution of the luminosity function of \( \text{Ly} \alpha \) emitters between \( z = 5.7 \) and \( z = 6.5 \) (Malhotra & Rhoads 2004; Stern et al. 2005), which has also been interpreted as evidence against percolation taking place at \( z \sim 6 \). Another promising (although observationally challenging) test of \( x_{\text{Hi}} \) is the \( \text{O} \) i absorption forest (Oh 2002): \( \text{O} \) i is an excellent tracer of neutral hydrogen, appears redward of the \( \text{Ly} \alpha \) forest, and remains unsaturated even if the IGM is highly neutral.

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