

Ly α Leaks in the Absorption Spectra of High-Redshift Quasi-Stellar Objects
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Please start each question (by number) on a new sheet of paper, write on only one side of the paper, and staple them together in order of question number when finished. Each part can be answered with a simple drawing and/or a few concise sentences.

1. (30 pts Total) Gunn–Peterson Effect, Epoch of Reionization, and Ly α Leaks

(a) What is the Ly α transition for hydrogen? Draw a simple energy diagram with labels and give the wavelength of the Ly α photon in angstroms.

(5 points) *The Ly α transition is the absorption (or emission) from hydrogen for the $n=1$ to $n=2$ energy levels. The wavelength of the transition is 1215.67 Å. The energy diagram is given in Figure 1.*

(b) Physically, what is the Epoch of Reionization? Roughly, at what redshift(s) do we think reionization takes place?

(10 points) *The Epoch of Reionization is the time span over which neutral hydrogen in the intergalactic medium first begins to become ionized. Prior to this time, on average there is not a significant enough density of ionizing photons from QSOs, AGN, and/or luminous galaxies to ionize the hydrogen. WMAP data suggest that localized reionization may have begun as early as $z = 17$, but QSO spectra show clearly that it is not complete until a redshift around $z = 6$. So, the epoch of reionization spanned the redshift range $6 \leq z \leq 17$.*

(c) Physically, what is the Gunn–Peterson Effect (GPE)? Describe in words the feature that you would see in a quasar spectrum due to the GPE. Draw an accurate “schematic” of the GPE feature in a $z = 7$ quasar spectrum showing the Ly α emission line of the quasar. Label both the Ly α emission line and the GPE feature, and provide the wavelength scale on your drawing.

(5 points) *The GPE results from Ly α absorption from neutral hydrogen and the expansion of the universe. If the IGM is uniformly neutral, then the optically thick Ly α lines completely blend together due to the Hubble expansion, i.e., $\lambda_{\text{obs}} = (1 + z)\lambda_{1215}$, resulting in zero transmission at all λ_{obs} . The GP trough is the region of a QSO spectrum which has zero flux blueward of the Ly α emission line.*

(5 points) *A schematic of a QSO spectrum with a GP trough is shown in Figure 2.*

(d) Describe what Ly α Leak features appear as in quasar spectra. Add a few schematic Ly α Leaks to your quasar diagram. Label them and give the approximate redshifts at which you have drawn them.

(5 points) *If there are regions in which the neutral hydrogen is partially or fully ionized, then Ly α photons can be transmitted through this region (the “leaking” effect). Depending upon the redshift of this region, these transmitted Ly α photons will be present in the spectrum at $\lambda_{\text{obs}} = (1 + z)\lambda_{1215}$. Since the surrounding wavelength regions have zero flux due to the GPE, these Ly α “leaks” appear as small “emission” lines in QSO spectra. See Figure 2 for the schematic of Ly α leaks in a spectrum.*

2. (25 pts Total) The Patch–to–Uniform Transition

(a) Briefly in your own words, describe the patch–to–uniform transition of the intergalactic medium (IGM).

(10 points) *“Patches” refer to regions where hydrogen is ionization (partially or fully). For a period of cosmic time, these regions are physically separated from one another, and therefore are distributed in a quasi-random patchy topology. As the universe expands, the patches expand via the Hubble flow. But also, the density of hydrogen decreases, such that the patches grow faster than the Hubble flow. At some point in time, they begin to overlap and intersect. Eventually, the ionized regions become fairly uniformly distributed and the situation has reversed such that now there is a patchy network of neutral regions embedded in a somewhat uniform topology of ionized hydrogen.*

(b) Draw a very simple diagram of the topological evolution of the IGM near this transition epoch. Include three panels, (1) a sketch of the topology during the “early stages”, (2) a sketch of the topology in the midst of the

transition, and (3) a sketch of the topology at the “end stage” of the transition. Label each panel, “early stages”, “transition”, and “end”, respectively. Label your diagrams, including which regions are primarily ionized and which parts are primarily neutral. Also label which IGM regions would give rise to the GPE and the IGM regions that would give rise to Ly α Leaks.

(10 points) See Figure 3. The main point here is that (1) in the “early stages” the ionized regions comprise a small volume filling factor of the IGM, (2) in the “transition stage”, the volume filling factors of the ionized and neutral IGM are roughly equal, with the ionized regions just beginning to overlap, and (3) in the “end stages”, the ionized regions comprise the predominant volume filling factor.

(c) If you observed a quasar spectrum and the line of sight was probing the “early stages”, would you expect to see primarily the (i) GPE feature, (ii) the GPE feature and Ly α leaks, or (iii) the Ly α forest. And for the “transition” stage? And for the “end stage”?

(5 points) Early: one sees GPE. Transition: one sees GPE + Ly α Leaks. End: one sees Ly α forest.

3. (15 pts Total) Equivalent Width Function

(a) In your own words, what is the equivalent width function, $n(W, z)$?

(5 points) The equivalent width function, also called the number density distribution function, $n(W, z) = dN/dWdz$, is defined as the number of “systems” per unit equivalent width per unit redshift. In practice, this is computed by defining an equivalent width bin of width dW and a redshift bin of width dz and counting the number of systems in these bins. The values of W and z are often taken as the bin midpoint or the average of the data points in the bin.

(b) In Table 1 (flip side), an imaginary list of observed Ly α Leaks is presented for the survey. From these data compute $n(W, z)$ in the redshift bin $5.7 \leq z \leq 6.0$ and equivalent width bin $0.3 \leq EW < 1.0$ Å. Estimate the uncertainty $\sigma[n(W, z)]$. Show your work and all steps clearly.

(10 points) The equivalent width bin is $dW = 1.0 - 0.3 = 0.7$. The redshift bin is $dz = 6.0 - 5.7 = 0.3$. From Table 1, the number of Ly α Leak systems in these bins is $dN = 6$. Thus, $n(W, z) = dN/dWdz = (6)/(0.7)(0.3) = 28.6$. Applying Poisson statistics, the uncertainty is $\sigma[n(W, z)] = \sqrt{dN}/dWdz = 2.45/(0.3)(0.7) = 11.7$. Note that $\sigma[n(W, z)] \neq \sqrt{28.6}$.

4. (30 pts Total) Interpreting the Leaks: Ionization or density inhomogeneities?

(a) What does Figure 3 demonstrate? What do the authors infer from this result?

(5 points) To repeat the authors own words, “The larger leaks evolve faster.” Thinking about this a bit, larger leaks are higher equivalent width systems (in emission). But, what is the sense of this evolution? It means that larger regions (greater line of sight path lengths) or more highly ionized regions (which could be the result of higher intensity UV radiation fields or lower density voids) evolve most rapidly with redshift. The sense of the redshift evolution is that as redshift increases, the number of larger equivalent width systems decrease the most rapidly.

(b) The authors compare two competitive scenarios of what gives rise to the inhomogeneities in the high redshift IGM as inferred from GPE and Ly α Leak statistics [i.e., the equivalent width function, $n(W, z)$, and the cumulative equivalent width function, $n(> W, z)$]. Briefly, what are these two scenarios (i.e., in each scenario what is “uniform” and what is not “uniform”)?

(10 points) In both scenarios, the Ly α Leaks arise from ionized regions that comprise a small filling factor of the IGM, which means they are embedded in a neutral IGM medium. The first scenario is that the density of IGM hydrogen gas is uniform, whereas the ionized regions arise due to a non-uniform ionization field, i.e., discrete high ionization sources, such as galaxies, QSOs, and AGN, and that these carve out regions analogous to Stromgren spheres. The second scenario is that the ionization field is uniform, but that the density of hydrogen gas in the IGM is non-uniform. In high density regions, the gas remains neutral; in low density regions, the gas is easily ionized—the Ly α Leaks arise in the low density regions of the IGM.

(c) Which scenario do the authors favor as being the prominent effect, i.e., most consistent with the observed statistical properties as measure in their data, and why? (HINT: Consider the arguments the authors quantitatively apply to determine upper limit on the contribution to the EW statistics for one of the scenarios to rule it out.)

(15 points) The authors favor the uniform ionization field and the inhomogeneous IGM density field. Consider what is inconsistent with the non-uniform ionization field. First, the authors demonstrate that the ionization regions surrounding galaxies embedded in neutral IGM at $z \simeq 6$ can contribute to only 20% of the number of observed leaks. Second, they show that large leaks can arise only from the highest ionization sources; this means the patch to uniform transition would have to occur at $z > 6$, but at $z = 6$ the IGM is primarily neutral, as observed via the GP trough. Now consider what is consistent with the non-uniform IGM density. The authors show that the equivalent width distributions of Ly α Leaks are consistent with the mass functions of galaxy clusters, assuming that the equivalent widths are proportional to the co-moving volume probed by the QSO sightlines. They also show that the equivalent width distributions of Ly α Leaks are consistent with those obtained using mock spectra through cosmological simulations. The beauty of this interpretation is that the equivalent width function are a sensitive probe of cosmological parameters.

TABLE 1
Ly α LEAKS

redshift	EW, Å
5.609	1.20
5.698	0.35
5.702	0.10
5.711	0.31
5.715	0.65
5.719	1.12
5.830	0.43
5.845	0.75
5.890	0.27
5.913	0.83
5.981	1.31
5.987	0.92
5.990	0.27
6.210	0.34
6.332	1.09
6.451	0.54

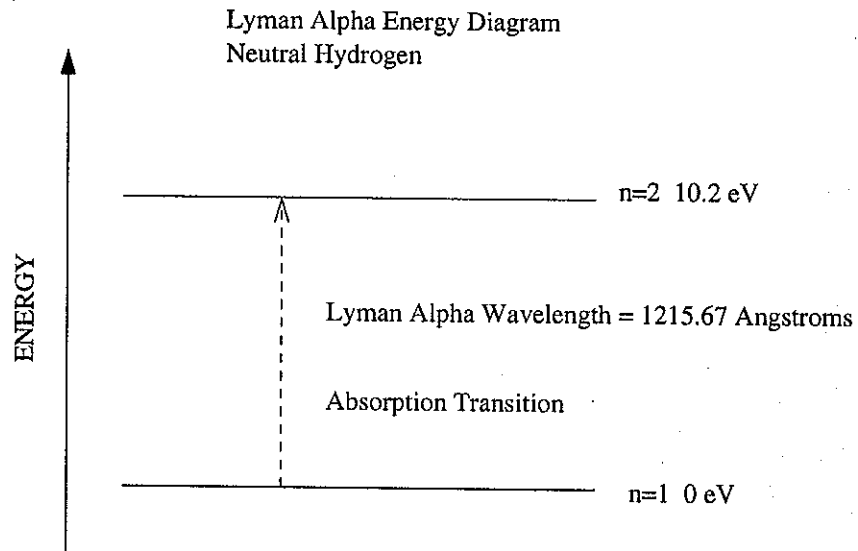


Fig. 1.— Energy diagram of hydrogen.

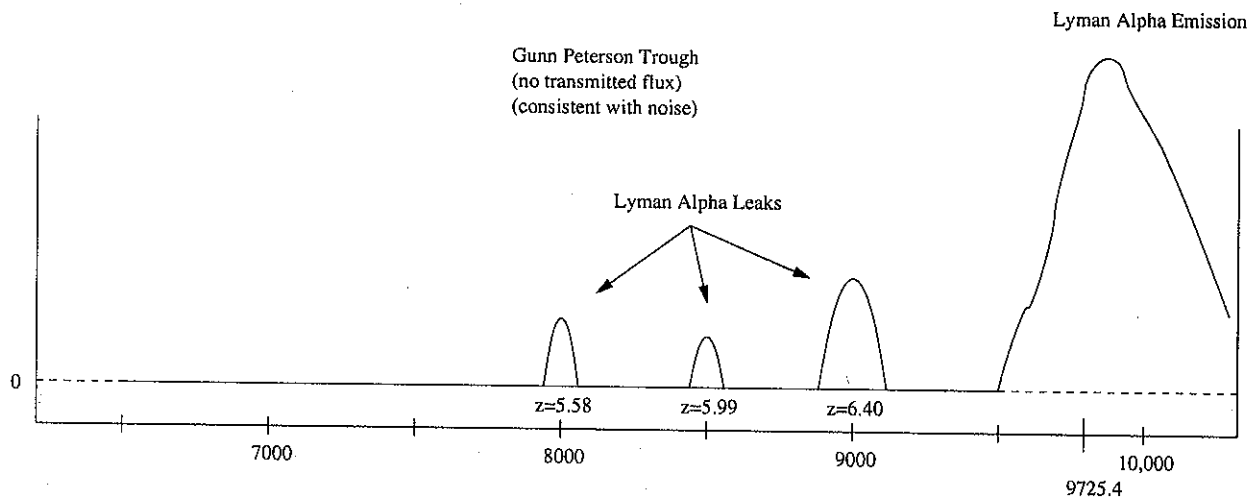


Fig. 2.— Redshift $z = 7$ QSO spectrum with GPE and leaks. Emission line peaks at 9725 Å. The GP trough is zero flux (consistent with noise) blueward of the emission line. Three leaks are shown, at $z = 5.58$, 5.99, and 6.40.

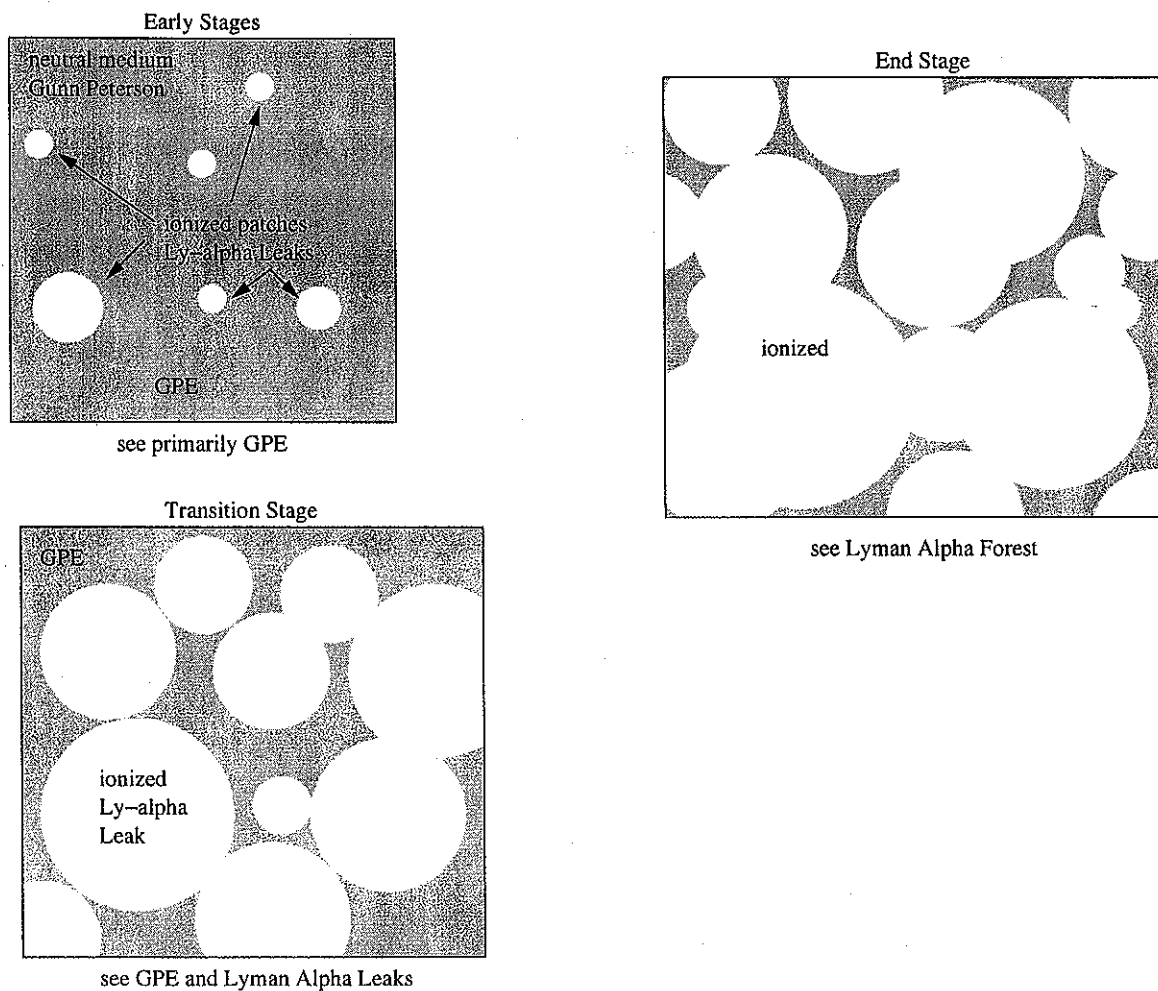


Fig. 3.— Topology of IGM. Note that ionization sources are not drawn into the ionization patches; though some may have begun this way, the interpretation of the paper is that it is the low density of the regions that allow them to become ionized in a uniform ionization field.

Ly α LEAKS IN THE ABSORPTION SPECTRA OF HIGH-REDSHIFT QUASI-STELLAR OBJECTS

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ABSTRACT

Spectra of high-redshift QSOs show deep Gunn-Peterson absorptions on the blue sides of the Ly α emissions lines. They can be decomposed into components called Ly α leaks, defined to be emissive regions in complementary to otherwise zero-flux absorption gaps. Just like Ly α absorption forests at low redshifts, Ly α leaks are easy to find in observations and contain rich sets of statistical properties that can be used to study the early evolution of the intergalactic medium (IGM). Among all properties of a leak profile, we investigate its equivalent width in this paper, since it is weakly affected by instrumental resolution and noise. Using 10 Keck QSO spectra at $z \sim 6$, we have measured the number density distribution function $n(W, z)$, defined to be the number of leaks per equivalent width W and per redshift z in the redshift range 5.4–6.0. These new observational statistics, in both the differential and cumulative forms, fit well to hydrodynamic simulations of uniform ionizing background in the Λ CDM cosmology. In this model, Ly α leaks are mainly due to low-density voids. It supports the early studies that the IGM at $z \approx 6$ would still be in a highly ionized state with a neutral hydrogen fraction $\approx 10^{-4}$. Measurements of $n(W, z)$ at $z > 6$ would be effective to probe the reionization of the IGM.

Subject headings: cosmology; theory — intergalactic medium

1. INTRODUCTION

The absorption spectra of QSOs at low redshift show Ly α forests, which have played an important role in the understanding of the physical status of diffuse cosmic baryon gas and the ionizing background. At redshift $z > 5$, however, they no longer show forest features, but consist of complete absorption troughs separated by the spikes of transmitted flux (e.g., Becker et al. 2001; Fan et al. 2006). That is, although the cosmic hydrogen gas at $z > 5$ is, on average, opaque for Ly α photons, there are many tiny regions that are Gunn-Peterson transparent and lead to Ly α photon leaking.

The nature of the leaking is crucial to an understand of the physics of reionization. According to the commonly accepted scenario of reionization, at early stages, only isolated patches around ionizing sources are highly ionized. The subsequent growing and overlapping of the ionizing patches lead to a uniform ionizing background and the end of reionization (e.g., Ciardi et al. 2003; Sokasian et al. 2003; Gnedin 2004; Mellema et al. 2006). The ionization fraction of the IGM and the ionizing radiation undergo an evolution from highly nonuniform patches to a quasi-homogeneous field. Before the patch-to-uniform transition, only ionized patches would be transparent to Ly α photons. After the transition, the low-density voids will also be Gunn-Peterson transparent. Therefore, the origin of Ly α leaks will constrain the epoch of the patch-to-uniform transition. In this Letter, we study the origin of Ly α leaks in the observed spectra of QSOs at $z \approx 6$.

Several statistics have been introduced to describe the transmitted flux of Ly α absorption at high redshifts, including the probability distribution function (PDF) of the flux (Fan et al. 2002; Becker et al. 2007), the distribution of the size of dark gaps (Songaila & Cowie 2002; Fan et al. 2006), and the largest peak width distribution (Gallerani et al. 2007). We focus on the profile of the leaking features in the transmitted flux. We fit these statistical features with samples of a hydrodynamic

simulation with a uniform ionizing background and analyze the possibility of explaining the leaks by ionized patches embedded in neutral IGM background.

2. SAMPLES

1. *Observational spectra of high-redshift QSOs.* The observational spectra used here are 10 of the 12 Keck spectra of QSOs at redshift $z > 5.8$ compiled in Fan et al. (2006). We excluded two broad absorption line (BAL) QSOs. The data have a uniform resolution of $R \sim 4000$ and are rebinned to a resolution of $R = 2600$. To avoid the mixing of Ly β absorption and the effect of the QSO's H II region, only the rest-frame wavelengths between 1050 to 1170 Å are used. To study the evolution of Ly α leaks, we divide the spectra into two redshift bins, $5.4 < z \leq 5.7$ and $5.7 < z \leq 6.0$. The observed flux f_{obs} is normalized with a power-law continuum $f_{\text{con}} \propto \nu^{-0.5}$. The noise level of transmitted flux $F \equiv f_{\text{obs}}/f_{\text{con}}$ is about 0.018 ± 0.012 and 0.014 ± 0.008 for above two redshift bins, respectively. For more details, we refer the reader to Fan et al. (2006).

2. *Simulation samples.* We simulate Ly α absorption spectra with a hybrid gas/dark matter code based on the weighted essentially non-oscillatory (WENO) scheme (Feng et al. 2004). The simulation is performed in a comoving box of $100 h^{-1}$ Mpc with a 512^3 mesh. We use the concordance Λ CDM cosmology model with parameters of $\Omega_m = 0.27$, $\Omega_b = 0.044$, $\Omega_\Lambda = 0.73$, $h = 0.71$, and $\sigma_8 = 0.84$, and a spectral index $n = 1$.

It has been shown that the observed dramatic decrease and abnormally large scatter of Gunn-Peterson optical depth at $z \approx 6$ (Fan et al. 2006) can be well fitted by models of a uniform ionizing background (Lidz et al. 2006; Liu et al. 2006). That is, the large scattering of Gunn-Peterson optical depth may still be mainly due to the inhomogeneity of the IGM density field. Therefore, we investigate whether such a uniform ionizing background can explain the leaks. In this context, the uniform photoionization rate is adjusted to yield the same mean optical depth as observational data at the redshifts considered. A thermal energy of $T = 3 \times 10^4$ K is added at $z = 10$, and only

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adiabatic cooling and shock heating are followed. With this method, the photoionization rates are found to be equal to 0.63 and 0.33 in units of 10^{-12} s^{-1} at redshifts of $z = 5.55$ and 5.85 , respectively, and the corresponding neutral hydrogen fractions are 3×10^{-5} and 7×10^{-5} . The simulated spectra were smoothed with a Gaussian window of a FWHM corresponding to $R \sim 4000$ and were rebinned to pixels of the size $R = 2600$. We added Gaussian noises to the rebinned fluxes, with variances equal to the observational noise level.

3. STATISTICS OF $\text{Ly}\alpha$ LEAKS

1. *Identification of $\text{Ly}\alpha$ leaks.* $\text{Ly}\alpha$ leaks are identified as contiguous pixels where the fluxes have a maximum flux larger than 2σ or 3σ of the local noise level. The boundaries of a leak are defined as positions where the fluxes are smaller than a threshold F_{th} , or are the minimum between the neighboring leaks. That is, if there are two local maximums above 2σ or 3σ of the noise level, each one is identified as a leak. We take the threshold $F_{\text{th}} = 0.02$ in this Letter. Note that the identification of a leak depends mostly on the condition of the maximum flux (see discussion on Fig. 1 below). With this method, we decompose the transmitted fluxes between Gunn-Peterson troughs into $\text{Ly}\alpha$ leaks of different profiles. The $\text{Ly}\alpha$ leaks contain information that is different from the size of dark gaps and largest peak width, both of which measure only length scales.

To test the identification condition, we count the number of fake leaks due to noise in 100 simulation samples. The percentage of fake leaks are 2.3% (13%) and 0.4% (1.4%) for the 2σ and 3σ identifications, respectively, in the redshift range $5.4-5.7$ ($5.7-6.0$). Similarly, we also count the number of missed leaks due to noise. The percentage of such missing leaks are 5% (8%) and 15% (22%) for the 2σ and 3σ identifications, respectively, in the redshift range $5.4-5.7$ ($5.7-6.0$). The fluxes of missing leaks are generally around F_{th} . Therefore, the leak identification with $F_{\text{th}} = 0.02$ is statistically reliable. In the 10 Keck spectra, there are a total of 173 and 147 leaks in the redshift range $5.4 \leq z \leq 5.7$, and 39 and 32 leaks in $5.7 < z \leq 6.0$, for the 2σ and 3σ identifications, respectively. The fluxes of the smallest leaks are a little higher than $F = 0.02$, while big leaks can have $F \approx 0.3$.

2. *Equivalent width functions.* Similar to emission and absorption lines, we can measure the profile of $\text{Ly}\alpha$ leaks with the equivalent width, which is defined as the area under its flux profile, $W = \int F d\lambda$, where the integral is over the range between the boundaries. For our observed samples, W spans the range from $0.06 \text{ \AA}$ to about $5 \text{ \AA}$. In general, the equivalent width W measures the strength of the leaking, or the Gunn-Peterson optical depth within the leaking regions. The statistical description we used is the equivalent width function $n(W, z)$, which is the number of leaks of W at redshift z per unit W per unit z . The equivalent width function reflects the distribution of the strength of leaking.

We count the observed W into 15 bins with logarithm size $\Delta \ln W = (1/15) \ln(10/0.01)$. The results are shown in Figure 1, which is for leaks at redshifts of $5.4-5.7$ (top) and $5.7-6.0$ (bottom), and the 2σ (left) and 3σ (right) identification. The error bar is of Poisson fluctuation. The functions $n(W, z)$ are weakly dependent on the identification. Although the total numbers of leaks of the 2σ and 3σ samples are different, the shape of $n(W, z)$ for both samples are about the same. As expected, for large leaks of $W > 0.5 \text{ \AA}$, the functions $n(W, z)$ are

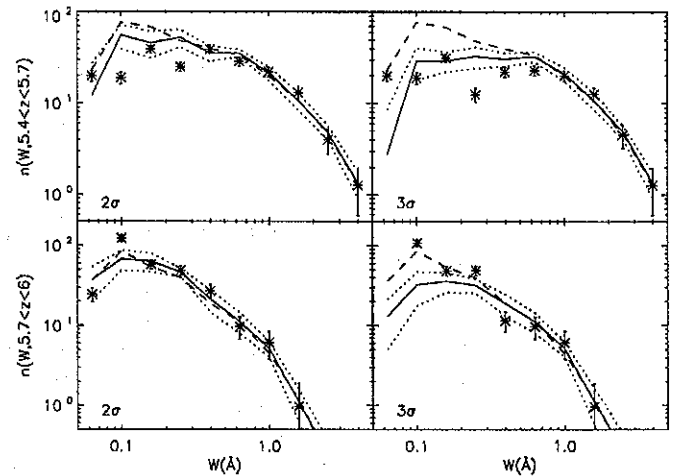


FIG. 1.—Equivalent width function $n(W, z)$ for leaks of 2σ (left) and 3σ (right) identification at redshift ranges $z = 5.4-5.7$ (top) and $5.7-6.0$ (bottom). The data points are from 10 Keck QSO spectra. The error bars are from Poisson fluctuation. The solid lines are calculated with 100 simulated spectra; dotted lines are the range of variance over the 10 subsets, each of which contains 10 spectra; dashed lines are for samples without noise. The noise has little effect on equivalent width W .

independent of the 2σ or 3σ condition, while for small leaks of $W < 0.5 \text{ \AA}$, the function $n(W, z)$ of 3σ is a little lower than that of 2σ .

Figure 1 also shows the results given by 100 simulation samples. The solid curves show the mean of the samples, and the dotted lines give the jackknife error estimator, derived by dividing the 100 samples into 10 subsamples and computing the variance over the 10 subsamples. We see that the distributions of $n(W, z)$ of simulation samples are generally good fits to the observed samples. To test the effect of noise, we also calculated the function $n(W, z)$ of simulation samples without the addition of noise, and the results are shown in Figure 1 as dashed lines. Without the noise addition, the leaks are identified as local maximums above $F_{\text{th}} = 0.02$. Figure 1 shows that the noise has no effect on big leaks ($W > 0.5 \text{ \AA}$), while for small leaks ($W < 0.5 \text{ \AA}$), samples without the noise addition give a higher number of leaks than samples with the noise addition. This is because the identification condition of 2σ and 3σ is more rigorous than the condition of $F_{\text{th}} = 0.02$. Therefore, the effect of noise on $n(W, z)$ does not change the consistence between observed and modeled $n(W, z)$. This is because W measures the area of the profiles.

We see from Figure 1 that a few data points at small W show fluctuation around the simulation result. It is probably caused by the binning. To solve this problem, we calculate the cumulative equivalent width function, defined as $n(> W, z) = \int_W n(W, z) dW$, which is less dependent on the binning. Since the distributions of leaks of 2σ and 3σ identification are similar, only the 2σ identification condition is applied. The results are presented in Figure 2. The solid curves show the mean of the simulated samples, and the dotted lines give the jackknife error estimator as in Figure 1. It shows clearly that the cumulative width functions of observed leaks are smooth and give a better fitting with simulation samples.

Figure 3 presents $n(> W, z)$ versus z for leaks of $W = 0.4, 1, \text{ and } 1.6 \text{ \AA}$. The redshift evolution of leaks with larger W is more significant than smaller W leaks. This is natural in the low-density voids scenario. The larger voids have lower probability and are events on the tail of the PDF of voids. They

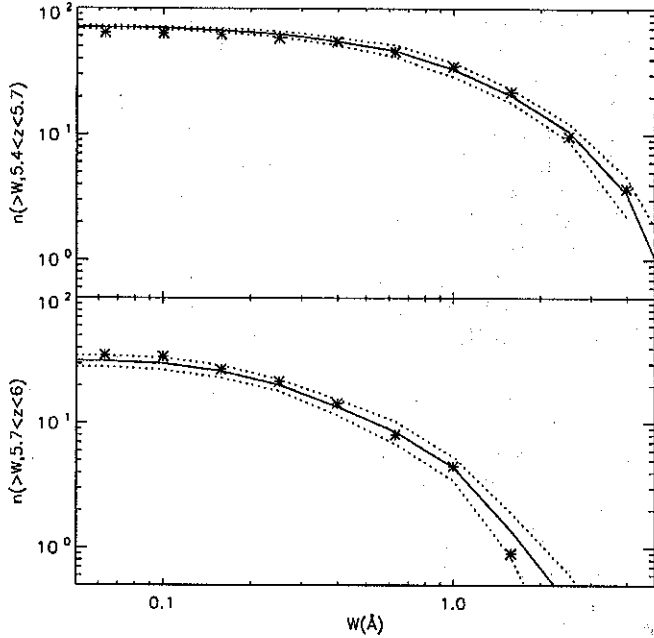


FIG. 2.—Cumulative width function $n(>W, z)$ for leaks at redshift ranges $z = 5.4-5.7$ (top) and $5.7-6$ (bottom). The data points are from 10 Keck QSO spectra. The solid lines are from 100 simulated spectra; dotted lines are the range of variance over the 10 subsets, each of which contains 10 spectra.

underwent a stronger evolution than small voids at high redshifts. At redshift $z > 6$, there are only very few leaks identified from observational data, and therefore we do not extend the analysis to $z > 6$.

Since all leaks in simulated spectra are due to low-density voids, the results show that the distribution of observed leaks are consistent with low-density voids, assuming the uniform ionizing background. It is interesting to point out that the tail of the cumulative width function shown in Figure 2 is close to Gaussian distribution with respect to the logarithm W . Therefore, $n(>W, z)$ approximately has a lognormal tail of W .

3. *Ionized patches.* We now estimate the Ly α leaking due to the ionized patches around ionizing sources. Considering a simple model, ionizing sources embed in a fully neutral IGM at high redshift. The scale of ionizing patches can be estimated with a radius $R = R_s[1 - \exp(-t/t_{\text{rec}})]^{1/3}$, where R_s is the Strömgren sphere radius and t_{rec} and t are respectively the recombination time and the active age of the ionizing source. It has been shown that due to the retardation effect of photon propagation, the scale R is actually an upper limit to the ionized volume (Shapiro et al. 2006; Qiu et al. 2007). The retardation effect is more apparent for clustered sources (Qiu et al. 2008). Moreover, it is also shown that the fraction of H I within an ionized sphere is generally larger than 10^{-6} unless the intensity of sources $\dot{N} > 10^{55} \text{ s}^{-1}$ (Qiu et al. 2007).

It has been shown that the damping wing of the neutral IGM absorption makes ionized patches opaque to Ly α photons if the size is too small (Miralda-Escude 1998). This effect is more significant if a small fraction of H I remains in patches. For instance, an ionized patch with a neutral fraction of 5×10^{-6} around a galaxy at $z = 6$ can yield a flux $F = 0.02$ only if the comoving radius $R \geq 3.5 h^{-1} \text{ Mpc}$, or $\dot{N} \geq 9 \times 10^{53} \text{ s}^{-1}$, which requires a luminosity $L \geq 1.6 \times 10^{10} L_\odot$ if assuming a spectra of $L_\nu \propto \nu^{-3}$. Here we also assume that all the ionizing radiation of a galaxy is capable of contributing to the ionizing sphere, and the luminosity $L \geq 1.6 \times 10^{10} L_\odot$ gives a lower

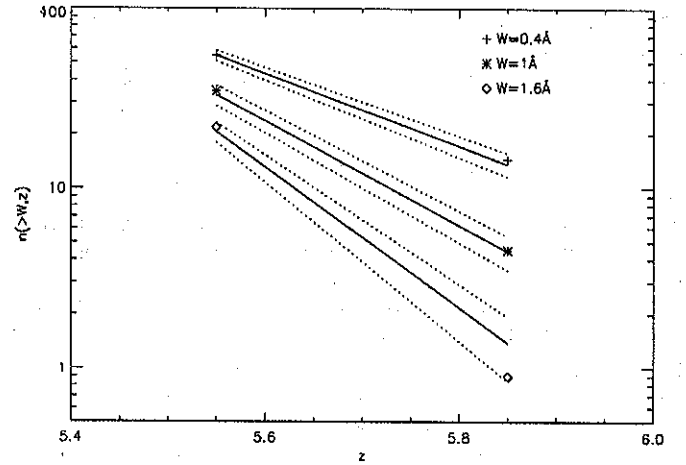


FIG. 3.—Redshift evolution of cumulative width function $n(>W, z)$ of leaks of $W = 0.4, 1$, and 1.6 Å (top). The data are taken from Fig. 2. The larger leaks evolve faster.

limit to the required luminosity to produce a leak with $F = 0.02$.

With these results, one can estimate the number of leaks with $F \geq 0.02$ due to galaxies by using the luminosity function of galaxies at $z = 6$ (Bouwens et al. 2006). The probability that a line intercepts patches at a comoving impact parameter $r = 1.5 h^{-1} \text{ Mpc}$ (since the cross radius should be larger than $3.5 h^{-1} \text{ Mpc}$, we should use a smaller impact radius) for galaxies with luminosity $> 1.6 \times 10^{10} L_\odot$ is (e.g., Peebles 1993)

$$\frac{dN}{dz} = \frac{\pi r^2 \phi(> 1.6 \times 10^{10} L_\odot) c}{H(z)} \sim 7.7, \quad (1)$$

where $\phi(> 1.6 \times 10^{10} L_\odot)$ is the comoving number density of galaxies with luminosity $> 1.6 \times 10^{10} L_\odot$. On the other hand, Figures 1 and 2 show that the number density of leaks with $F \geq 0.02$ at $5.7 < z < 6$ is ≈ 35 . Therefore, if the IGM $z = 6$ is mostly neutral, and the only ionized regions are the patches around galaxies, the leaks of $F \geq 0.02$ given by the ionized patches of galaxies would be no more than 20% of the observed result.

4. DISCUSSIONS AND CONCLUSIONS

The transmitted fluxes between Gunn-Peterson troughs of high-redshift QSO absorption spectra contain rich structures that can be decomposed into Ly α leaks. The Ly α leaks have profiles similar to emission lines and can be measured by equivalent width W . The equivalent width functions $n(W, z)$ are effective statistical measurements of the process of reionization. We show that the equivalent width functions of the observed spectra at redshifts $5.4 < z < 6.0$ can be well fitted by hydrodynamic simulation of the Λ CDM cosmology, assuming the ionizing background to be uniform. In this model, all the Ly α leaks are leaking through low-density voids.

The mean transmitted flux at z is given by $\bar{F} \propto \int n(W, z) W dW$. Therefore, by adjusting the photoionization rate to match the observed Gunn-Peterson optical depth, the mean of W for simulation samples should be the same as the observations. Thus, Figure 1 actually shows that once we adjusted the mean flux to be the same as observational data, the simulation yields the same distribution of the observed W . In other words, the scattering of W is caused by the fluctuations of the

mass density field of H I. Therefore, a small inhomogeneity of the ionizing background would be allowed. That is, the distribution of W would still be able to be fitted with a fluctuating ionizing background if its variance is much less than that of H I.

In addition to the distribution of W , the evolution of W is also helpful when differentiating models. For example, in the voids scenario, the evolution of W reflects the evolution of low-density voids, while for ionized patches, it reflects the evolution of the UV luminosity function of ionizing sources.

We show that the ionized patches of galaxies embedded in a fully neutral IGM at redshift $z \approx 6$ are not enough to produce the observed leaks. We also show that leaks can only be produced by patches around strong ionizing UV photon sources, but not weak sources. In particular, big leaks ($W > 0.5 \text{ \AA}$, or $F > 0.1$) have to come from very strong sources. Therefore, at higher redshift, Ly α leaks only probe strong ionizing sources. Thus, from the existence of many big leaks at $z \leq 6$, we can conclude that the patch-to-uniform transition of the ionizing background would occur at $z > 6$, and most of the IGM at $z \approx 6$ is still in a highly ionized state of neutral fraction $f_{\text{H I}} \approx 10^{-4}$. This result is consistent with the analysis of the transmitted flux PDF (Becker et al. 2007), the QSO proximity zones (Lidz et al. 2007), and the luminosity function of Ly α -emitting galaxies (Dijkstra et al. 2007).

It should be pointed out that the resolution of the observed data is low, $\sim 3 \text{ \AA}$, which corresponds to a comoving size

$\approx 0.7 h^{-1} \text{ Mpc}$. In contrast, most of the simulated leaks possess an intrinsic width $< 3 \text{ \AA}$. Thus, the low-resolution data provide only a test of smoothed leaking features. One cannot see whether the smoothed features are due to individual or clustered leaks. Higher resolution spectra would be able to test not only the width functions, but also the spatial correlations of the leaks. They can also provide other measurements of Ly α leaks, such as the FWHM, which will be effective to confront observational data with models.

The statistics of Ly α leaks at redshifts ≤ 6 are actually the statistics of voids formed in the early universe. The equivalent width functions $n(W, z)$ of Ly α leaks are similar to the mass function of galactic clusters. Thus, one can expect that the width functions of voids are sensitively dependent on cosmological parameters and play a similar role as the mass function of clusters. For instance, the formation of large voids is found to be sensitively dependent on the mass parameter Ω_m (Miranda & de Araujo 2001). With data on leaks, we can set constraints on cosmological parameters at high redshifts. This approach will be reported separately.

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