LYα LEAKS IN THE ABSORPTION SPECTRA OF HIGH-REDSHIFT QUASI-STEMELLAR OBJECTS

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ABSTRACT

Spectra of high-redshift QSOs show deep Gunn-Peterson absorptions on the blue sides of the Lyα emissions lines. They can be decomposed into components called Lyα leaks, defined to be emissive regions in complementary to otherwise zero-flux absorption gaps. Just like Lyα absorption forests at low redshifts, Lyα 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 ~ 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 ΛCDM cosmology. In this model, Lyα leaks are mainly due to low-density voids. It supports the early studies that the IGM at z = 6 would still be in a highly ionized state with a neutral hydrogen fraction ≈ 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 Lyα 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 Lyα photons, there are many tiny regions that are Gunn-Peterson transparent and lead to Lyα 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 Lyα photons. After the transition, the low-density voids will also be Gunn-Peterson transparent. Therefore, the origin of Lyα leaks will constrain the epoch of the patch-to-uniform transition. In this Letter, we study the origin of Lyα leaks in the observed spectra of QSOs at z = 6.

Several statistics have been introduced to describe the transmitted flux of Lyα 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 ~ 4000 and are rebinned to a resolution of R = 2600. To avoid the mixing of Lyβ absorption and the effect of the QSO’s H α region, only the rest-frame wavelengths between 1050 to 1170 Å are used. To study the evolution of Lyα leaks, we divide the spectra into two redshift bins, 5.4 < z ≤ 5.7 and 5.7 < z ≤ 6.0. The observed flux f_{obs} normalized with a power-law continuum f_{cont} $\propto \nu^{-0.5}$. The noise level of transmitted flux F \equiv f_{obs}/f_{cont} 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 Lyα 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 ΛCDM 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 = 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 $3 \times 10^{-3}$ and $7 \times 10^{-3}$. 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 2 $\sigma$ or 3 $\sigma$ of the local noise level. The boundaries of a leak are defined as positions where the fluxes are smaller than a threshold $F_{\text{th}}$, or are the minimum between the neighboring leaks. That is, if there are two local maxima above 2 $\sigma$ or 3 $\sigma$ 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 2 $\sigma$ and 3 $\sigma$ 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 2 $\sigma$ and 3 $\sigma$ identifications, respectively, in the redshift range 5.4–5.7 (5.7–6.0). The fluxes of missing leaks are generally around $F_{\text{th}}$. 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 2 $\sigma$ and 3 $\sigma$ 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, $W = \int F \lambda d\lambda$, where the integral is over the range between the boundaries. For our observed samples, $W$ spans the range from 0.06 Å to about 5 Å. 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 2 $\sigma$ (left) and 3 $\sigma$ (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 2 $\sigma$ and 3 $\sigma$ samples are different, the shape of $n(W, z)$ for both samples are about the same. As expected, for large leaks of $W > 0.5$ Å, the functions $n(W, z)$ are independent of the 2 $\sigma$ or 3 $\sigma$ condition, while for small leaks of $W < 0.5$ Å, the function $n(W, z)$ of 3 $\sigma$ is a little lower than that of 2 $\sigma$.

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 maxima above $F_{\text{th}} = 0.02$. Figure 1 shows that the noise has no effect on big leaks ($W > 0.5$ Å), while for small leaks ($W < 0.5$ Å), samples without the noise addition give a higher number of leaks than samples with the noise addition. This is because the identification condition of 2 $\sigma$ and 3 $\sigma$ 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 consistency 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 $n(> W, z) = \int_n n(W, z) dW$, which is less dependent on the binning. Since the distributions of leaks of 2 $\sigma$ and 3 $\sigma$ identification are similar, only the 2 $\sigma$ 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, and 1.6 Å. 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
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 of \( W \). Therefore, \( n(> W, z) \) approximately has a lognormal tail of \( W \).

3. **Ionized patches**. We now estimate the Ly\( \alpha \) 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 \( R = R_s (1 - \exp (-t_{bend})))^{1/3} \), where \( R_s \) is the Strömgren sphere radius and \( t_{bend} \) 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 hydrogen within an ionized sphere is generally larger than \( 10^{-8} \) unless the intensity of sources \( N > 10^{19} \) 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\( \alpha \) photons if the size is too small (Miralda-Escude 1998). This effect is more significant if a small fraction of hydrogen remains in patches. For instance, an ionized patch with a neutral fraction of \( 5 \times 10^{-8} \) around a galaxy at \( z = 6 \) can yield a flux \( F = 0.02 \) only if the comoving radius \( R \geq 3.5 \) h\(^{-1} \) Mpc, or \( N \geq 9 \times 10^{19} \) s\(^{-1} \), which requires a luminosity \( L \geq 1.6 \times 10^{10} L_\odot \) if assuming a spectra of \( L_\alpha \sim \nu^{-3} \). 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 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\(^{-1} \) Mpc (since the cross radius should be larger than \( 3.5 \) h\(^{-1} \) Mpc, we should use a smaller impact radius) for galaxies with luminosity \( >1.6 \times 10^{10} L_\odot \) is (e.g., Peebles 1993)

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

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 \( \approx 35 \). 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\( \alpha \) leaks. The Ly\( \alpha \) 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 \( \Lambda \)CDM cosmology, assuming the ionizing background to be uniform. In this model, all the Ly\( \alpha \) 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 dis-
tribution 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 pro-
duced by patches around strong ionizing UV photon sources,
but not weak sources. In particular, big leaks ($W > 0.5$ Å, or
$F > 0.1$) have to come from very strong sources. Therefore, at
higher redshift, Ly$\alpha$ 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
$f_{\text{HI}} \approx 10^{-4}$. 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$\alpha$
emitting galaxies (Dijkstra et al. 2007).

It should be pointed out that the resolution of the observed
data is low, $\sim 3$ Å, which corresponds to a comoving size
$\approx 0.7 h^{-1}$ Mpc. In contrast, most of the simulated leaks possess
an intrinsic width $\lesssim 3$ Å. 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$\alpha$ leaks, such as
the FWHM, which will be effective to confront observational
data with models.

The statistics of Ly$\alpha$ leaks at redshifts $\leq 6$ are actually the
statistics of voids formed in the early universe. The equivalent
width functions $n(W, z)$ of Ly$\alpha$ 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 $\Omega_m$ (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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