Reionization of the Intergalactic Medium and the Damping Wing of the Gunn-Peterson Trough

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ABSTRACT

Observations of high-redshift quasars show that the IGM must have been reionized at some redshift \( z > 5 \). If a source of radiation could be observed at the rest-frame Ly\( \alpha \) wavelength, at a sufficiently high redshift where some of the IGM in the line-of-sight was not yet reionized, the Gunn-Peterson trough should be present. Longward of the Ly\( \alpha \) wavelength, a damping wing should be observed caused by the neutral IGM whose absorption profile can be predicted. Measuring the shape of this damping wing would provide irrefutable evidence of the observation of the IGM before reionization, and a determination of the density of the neutral IGM. This measurement might be hindered by the possible presence of a dense absorption system associated with the source.

Shortward of the Ly\( \alpha \) wavelength, absorption should be seen from the patchy structure of the IGM in the process of reionization, intersected in the line-of-sight. We show that a complete Gunn-Peterson trough is most likely to continue to be observed through the epoch where the IGM is partially ionized. The damping wings of the neutral patches should overlap if the proper pathlength through an ionized region is less than \( 1h^{-1}\text{Mpc} \); even in larger ionized regions, the characteristic background intensity should be low enough to yield a very high optical depth due to the residual neutral fraction, although occasionally some flux may be transmitted through large, underdense voids within an ionized region. The case of the He\( \text{II} \) reionization is also discussed, and we argue that helium was already doubly ionized by \( z = 3 \) throughout the IGM.

The recently discovered afterglows of gamma-ray bursts might soon be observed at the very high redshifts required for these observations. Their featureless continuum spectrum and high luminosities make them ideal sources for studying absorption by the IGM.

Subject headings: galaxies: formation - large-scale structure of universe - quasars: absorption lines
1. Introduction

Observations of the spectra of high-redshift quasars blueward of the hydrogen Ly$\alpha$ line have demonstrated so far that the universe was already ionized by $z \simeq 5$, the highest redshift at which any sources have been found so far (Schneider, Schmidt, & Gunn 1991; Franx et al. 1997). If the intergalactic medium (hereafter IGM) in the line-of-sight to a source was neutral, the resonance scattering at the wavelength of the Ly$\alpha$ line should cause the “Gunn-Peterson trough” (Gunn & Peterson 1965), with an extremely high optical depth that would entirely absorb the flux from the source for any reasonable density of the IGM. At the same time, we expect that the known sources of ionizing photons (comprising quasars, stellar objects and hot gas) started to form much later than the recombination epoch, unless the amplitude of density fluctuations was much larger on small scales than predicted by all the models of structure formation. This implies the IGM should have been reionized at some point. In fact, the COBE measurement of the electromagnetic spectrum of the microwave background (with a limit on the $y$ parameter $y < 1.5 \times 10^{-5}$; Fixsen et al. 1996), as well as the presence of the Doppler peak in the intensity fluctuations, show that the IGM was reionized at $z \sim < 300$ (Wright et al. 1994; Hu & Sugiyama 1994; Tegmark & Silk 1995).

It is generally expected that the reionization was caused by the ionizing radiation from galaxies and active galactic nuclei. This implies that the IGM should have been reionized inhomogeneously, with every source ionizing first its immediate vicinity; the ionized bubbles would then fill a growing fraction of the volume in the universe until they overlap (Arons & Wingert 1972). Models of structure formation predict that reionization did not occur at extremely high redshift, but most likely at $z \lesssim 30$, given the epoch when the collapse of small-scale density fluctuations led to the formation of the first galaxies where enough stars could form to reionize the IGM (e.g., Tegmark, Silk, & Blanchard 1994; Haiman, Rees, & Loeb 1996). If a source could be seen at a redshift higher than that when most of the IGM was reionized, we should obviously see the Gunn-Peterson trough. And at redshifts were the reionization is already complete, we observe the Ly$\alpha$ forest caused by the residual neutral fraction in the highly ionized IGM (in photoionization equilibrium with the background radiation), with density fluctuations originated in the gravitational collapse of gas in the developing large-scale structure.

Thus, the question that naturally arises here is: how does the transition from one regime to the other take place? What should we expect to see in a spectrum where the increasing optical depth of the Ly$\alpha$ forest with redshift turns into the Gunn-Peterson trough? This is the question that shall be addressed in this paper. Meiksin & Madau (1993) speculated that a new class of high column density absorbers might appear at redshifts higher than the epoch when the reionization was completed, due to the neutral patches left in the IGM. The possible observable signatures in the Ly$\alpha$ spectra of sources seen at the time when the IGM still had this patchy ionized structure will be investigated in more detail here.
2. The Red Damping Wing

We consider a source that is observed through a neutral IGM with uniform density. If the photons scattered in the Lyα resonance were in a perfectly narrow line, we would expect to see a sudden drop in the flux at the Lyα wavelength at the redshift of the source. In reality, the optical depth to Lyα scattering is broadened both by the velocity distribution of the atoms and the natural width of the line. When the IGM is mostly neutral, the intrinsic line width is the dominant effect. The resulting absorption profile was discussed in Miralda-Escudé & Rees (1997), but we reproduce this here for completeness.

Any fluid element along a velocity interval $dV$ along the line-of-sight (corresponding to the Hubble expansion velocity over a spatial interval $dx = dV/H(z)$) has its optical depth spread in the observed spectrum according to

$$\tau(V) = \left(\tau_0 v/c\right)R_\alpha/\pi/[(V/c)^2 + R_\alpha^2].$$

Here, $\tau_0$ is the Gunn-Peterson optical depth of the neutral IGM before broadening, and is given by

$$\tau_0 = 2.1 \times 10^5 [\Omega_b h(1 - Y)/0.03] [H_0 (1 + z)^{3/2}/H(z)] [(1 + z)/6]^{3/2},$$

where $Y$ is the helium abundance and $H(z)$ is the Hubble constant at redshift $z$. The IGM is assumed to contain all the baryons, with density $\Omega_b$ in units of the critical density. We have defined also $R_\alpha = \Lambda/(4\pi\nu_\alpha) = 2.02 \times 10^{-8}$, where $\Lambda = 6.25 \times 10^8$ s$^{-1}$ is the decay constant for the Lyα resonance, and $\nu_\alpha = 2.47 \times 10^{15}$ Hz is the frequency of the Lyα line. As a result of this broadening, the observed absorption profile, at a wavelength separation $\Delta\lambda$ on the red side of the Gunn-Peterson trough, should be given by

$$\tau(\Delta\lambda) = \tau_0 R_\alpha/\pi \int_{\Delta\lambda/\lambda}^{\infty} \frac{d(V/c)}{(V/c)^2 + R_\alpha^2}. \quad (1)$$

Since $\tau_0 \gg 1$, the shape of this profile can only be observed when $(\Delta\lambda)/\lambda \gg R_\alpha$, so we have

$$\tau(\Delta\lambda) = \tau_0 R_\alpha/\pi (\Delta\lambda/\lambda)^{-1} = 1.3 \times 10^{-3} \frac{\Omega_b h(1 - Y)}{0.03} \frac{H_0 (1 + z)^{3/2}}{H(z)} \frac{(1 + z)^{3/2}}{6} (\Delta\lambda/\lambda)^{-1}. \quad (2)$$

Notice that the damping wing of the Gunn-Peterson effect has the optical depth falling as the inverse of the wavelength separation, as opposed to the inverse-square law for the damped absorption lines caused by high column density systems. The reason is that as we increase the wavelength separation, a larger pathlength through the neutral IGM contributes significantly to the optical depth, providing therefore a larger effective column density.

If a source is found at very high redshift showing the Gunn-Peterson trough, the presence or absence of the damping wing with the predicted absorption profile can be an unambiguous test for the state of ionization of the intervening IGM. The observation of the Gunn-Peterson trough alone does not prove that a source is being observed behind neutral IGM, because the value of $\tau_0$ is so large that a small residual neutral fraction in a reionized IGM can reduce the transmitted flux to undetectable levels. If the damping wing is observed, an obvious immediate application will be to infer the parameter $\tau_0$ from the observed width. At very high redshifts, we can use the approximation $\Omega(z) \simeq 1$ independently of the value of $\Omega$ at present, so $H(z) \simeq H_0 \Omega^{1/2}(1 + z)^{3/2}$. Thus, by measuring $\tau_0$ we can infer the quantity $\Omega_b h \Omega^{-1/2}$. 
There are two possible caveats in the measurement of this quantity. The first is that if the source is observed at the epoch when the IGM is being reionized, some regions along the line-of-sight should be mostly ionized and some others should be neutral. If the Hubble velocity across the H II regions is small compared to the width of the damping wing, the form of the damping profile should be essentially indistinguishable from the case of the homogeneous medium (and in that case, the width of the damping wing measures the space-averaged density of the fraction of the IGM that is neutral), but if the velocity is comparable then there will be random variations in the shape of the damping wing depending on the distribution of neutral gas close to the source. From equation 2, the width of the damping wing should be \( \sim 1500 \text{Km s}^{-1} \), or \( \sim 1 h^{-1} \text{Mpc} \), at \( z = 5 \). Notice that if there is only an ionized region around the source itself, with the rest of the gas in the line-of-sight that contributes significantly to the damping wing being all neutral, this does not affect the measurement of \( \tau_0 \), but it only affects the redshift of the neutral gas closest to the source, which can be obtained from a two-parameter fit to the shape of the observed damping wing.

The second possible problem is that the neutral IGM may not be homogeneous. In particular, any source of light is likely to be within a system that has gravitationally collapsed, and if the source has not ionized the surrounding gas producing an expanding cosmological H II region, we should expect it to be surrounded by a halo of accreting neutral gas. In that case, an additional column density of neutral hydrogen is added, very close to the redshift of the source. One could always try to circumvent the problem by adding the “local” column density as a third parameter to the fit to the damping wing profile, but for a realistic accuracy of the spectrum the errors will of course greatly increase as more parameters are added to the fit.

As an example, we plot in Figure 1 the absorption profile on a source at \( z = 9 \) (solid line), for \( \tau_0 = 4.3 \times 10^5 \). We have used the exact expression for the profile of the damping wing due to the neutral IGM, presented in the Appendix, where we do not assume \( (\Delta \lambda)/\lambda \ll 1 \) (as in eq. 2), and we include the effect of the cosmological evolution of the Gunn-Peterson optical depth, and the exact expression for the cross section of the Ly\( \alpha \) resonance line. The correction on the optical depth relative to the approximation in eq. 2 is about 20% when \( \Delta \lambda/\lambda = 0.02 \), and reaches a factor of 2 at \( \Delta \lambda/\lambda = 0.06 \); it will therefore be important to use the exact expression in the Appendix for practical applications. We also plot in Fig. 1 the result of adding to the IGM optical depth an absorbing system with column density \( N_{HI} = 2 \times 10^{20} \text{cm}^{-2} \) at the source redshift \( z = 9 \) (dotted line). Finally, the dashed line shows again the IGM optical depth without any additional absorbing system, but with the parameters \( z = 9.009, \tau_0 = 4.9 \times 10^5 \), which provide the best fit to the dotted line. It is clear from this example that even with an accuracy of 1% in the determination of the shape of the damping wing, there is still a large error in the determination of \( \tau_0 \) if an absorber of unknown column density is present at the redshift of the source. However, one may be able to determine the source redshift independently (for example, from associated metal-line absorption), in which case the ambiguity between the hydrogen column density of an associated absorber and \( \tau_0 \) should be much reduced.
3. Flux Transmission on the Blue Side of the Gunn-Peterson Trough

Moving down in redshift from the source, a line-of-sight will characteristically traverse several cosmological H II regions and neutral patches over the redshift interval corresponding to the epoch when the IGM was being reionized. The process of reionization can be very complicated: the sources of ionizing photons may have a wide range of luminosities and may be short-lived, so some ionized regions will start recombining if their source fades, becoming partially neutral until they are ionized again by another source. The sources could be highly clustered, so the ionized regions may start being very small and due to faint, individual sources, and later grow to a much larger scale and be ionized by clusters of sources, while large neutral patches may still remain in the IGM. And of course, the H II regions expand into a highly inhomogeneous IGM which is gravitationally collapsing into new large-scale structures. The case of a source of constant luminosity surrounded by a homogeneous medium can be solved analytically (Shapiro & Giroux 1987).

An ionized region intercepted by the line-of-sight over a total length \( L_i \equiv V_i / H(z) \) may cause a “gap” in the Gunn-Peterson trough if the damping wings of two neutral patches on each side do not completely overlap. Taking the parameters used in Fig. 1, we see that if we require that at least a fraction \( e^{-1} = 0.36 \) of the flux be transmitted in the middle of the gap, then the length of the intersected ionized region must be at least \( V_i / c > 10^{-2} \) (because at a separation \( V/c = 5 \times 10^{-3} \) from the edge of a neutral zone, the optical depth of the damping wing in Fig. 1 is \( \tau = 0.5 \)). Since \( \tau_0 \propto (1 + z)^{3/2} \), this minimum size scales with redshift as \( V_i / c > 10^{-2} [(1 + z)/10]^{3/2} \) in the approximation of eq. 2, or a proper length \( L_i > 1 h^{-1} \) Mpc (these scales are also proportional to \( \Omega_b h (1 - Y) \), but we are setting this quantity to 0.03 in this section).

In order to observe any transmitted flux to the blue of the Gunn-Peterson trough on a source at redshift \( z_s \), some H II region of this size has to be present on the line-of-sight at a redshift \( 1 + z_i > 1 + z_\beta \equiv (1 + z_s)/1.18 \), since at lower redshifts the Ly\( \beta \) Gunn-Peterson trough blocks the flux anyway. If the last neutral patch in the line-of-sight is located at \( z_n > z_\beta \), then flux may be observable between the blue Ly\( \alpha \) damping wing due to this last neutral patch and the Ly\( \beta \) damping wing of the neutral IGM close to the source, and some additional small gaps may be observable due to large H II regions at \( z > z_n \). If \( z_n < z_\beta \), then only these gaps due to isolated H II regions may be observable.

The existence of ionized regions with a proper size larger than \( 1 h^{-1} \) Mpc for a substantial period of time before reionization was over depends, of course, on the type of sources causing the ionization. Large H II regions would be expected if the radiation was dominated by very luminous sources; the luminosity required to reach a proper size \( 1 h^{-1} \) Mpc at \( z = 10 \) is similar to that of the most luminous quasars known. Reionization by early galaxies has been considered more likely in the usual hierarchical models for structure formation (Tegmark, Silk, & Blanchard 1994, Haiman & Loeb 1997, MR97). In this case, large H II regions might still exist if the sources were highly clustered, probably in the sites of formation of the future galaxy clusters. Early galaxies might in fact be clustered on large scales due to a high biasing factor, which is expected if galaxies form in
density peaks and when the power spectrum has a slope close to \( n = -3 \), as is generally predicted to be the case on small scales (Bardeen et al. 1986). On the other hand, if reionization is caused by low-luminosity sources which are not highly clustered on a proper scale of \( 1h^{-1}\) Mpc, then by the time the ionized regions had overlapped to this scale there should be very few neutral patches remaining in the IGM, (except for the neutral regions that are dense and self-shielded, i.e., regions which are neutral because of their high recombination rate, rather than the lack of sources in their vicinity).

Whether any flux is actually seen on the blue side of the damping wing of the last neutral patch in a line-of-sight, or in any gap due to an isolated ionized region, depends of course on the neutral fraction in the ionized medium being low enough. The neutral fraction should be in ionization equilibrium with the radiation field from the sources in the H II region, and will cause a “Ly\(\alpha\) forest”, as observed up to \( z \lesssim 5 \) so far; even a very small neutral fraction can completely absorb any remaining flux that is left between the damping wings of the neutral patches.

To calculate the absorption in the ionized regions, let us parameterize the mean volume emissivity of ionizing photons as

\[
\epsilon = \frac{n_e}{t} N_r ,
\]

where \( n_e \) is the mean electron density in the ionized IGM and \( t \) is the age of the universe. Thus, when \( N_r = 1 \) the emissivity is such that one ionizing photon will be emitted for each electron over the age of the universe. Obviously, at the end of reionization the factor \( N_r \) should be greater than unity, both because the comoving emissivity should increase with time (and therefore the integrated number of emitted photons is less than \( \epsilon t \)), and because electrons can recombine several times during reionization, increasing the number of photons that need to be emitted. The photon intensity is typically \( \epsilon L_i/(8\pi) \) (where we take the typical mean-free-path of photons to be \( \sim L_i/2 \)), and the implied photoionization rate is \( \Gamma = \epsilon L_i \bar{\sigma}/2 \), where \( \bar{\sigma} \) is the photoionization cross section averaged over all emitted photons; for a typical power-law slope \( F_\nu \propto \nu^{-1.5} \) near the hydrogen ionization edge, \( \bar{\sigma} \sim 2 \times 10^{-18} \text{ cm}^2 \). In an H II region having the minimum size that allows flux to be transmitted (using as before the condition that the optical depth between the two damping wings reaches a value less than unity), the length is \( L_i = [c/H(z)](4\tau_0 R_\alpha/\pi) \) (see eq. 2). The neutral fraction in a region of average density is equal to \( \alpha n_e/\Gamma \), and the optical depth in the ionized region due to this neutral fraction is:

\[
\tau_i = \tau_0 \frac{\alpha n_e}{(n_e/t) N_r (\tau_0 R_\alpha/\pi) [c/H(z)] \bar{\sigma}} = \frac{\pi \alpha}{3c\bar{\sigma} R_\alpha N_r} \frac{360 T_4^{-0.7}}{N_r} .
\]

Here, \( T_4 \) is the temperature of the ionized gas in units of \( 10^4 \) K; the temperature dependence is due to the recombination coefficient. Notice that \( \tau_i \) is the optical depth in the H II region if the gas density is equal to the mean baryonic density. In reality, the gas density should of course fluctuate and the optical depth should consequently vary with wavelength over the interval of Ly\(\alpha\) absorption of the H II region.

Thus, we have found the result that the optical depth to Ly\(\alpha\) scattering in an ionized region
that is just large enough to emerge from the damping wings of the Gunn-Peterson trough is independent of redshift and of any cosmological parameters, and depends only on the dimensionless number \( N_r \), defined in eq. 3.

Let us explore more carefully the interpretation of \( N_r \). There are two different cases that need to be considered. In case I, the sources of ionizing photons turn on quickly enough so that recombinations are negligible compared to the number of photons that need to be emitted. Therefore, the IGM is reionized when one ionizing photon has been emitted for each electron, and \( N_r = \epsilon / \bar{\epsilon} \), where \( \bar{\epsilon} \) is the time-averaged comoving emissivity. Unless the sources are highly synchronized, \( N_r \) will not be larger than \( \sim a \) few. The other possibility, case II, is that reionization is limited by the rate at which electrons can recombine. In that case, \( N_r \) is simply the mean number of recombinations for each electron that take place over the age of the universe, \( t \): if the sources turn on over a time \( t_r \), each electron undergoes \( N_r (t_r / t) \) recombinations during the time \( t_r \), and the required emissivity is \( \epsilon = (n_e / t_r) N_r (t_r / t) = (n_e / t) N_r \). This mean number of recombinations is

\[
N_r = 0.91 \left( \frac{0.03}{\Omega B h} \right) \left( \frac{1 + z}{10} \right)^{3/2} \frac{\langle n_e^2 \rangle}{\langle n_e \rangle},
\]

where the last term is the electron clumping factor. Thus, at a fixed redshift, the only way for \( N_r \) to be large is that the IGM be highly clumped, and the clumps need to have a large covering factor through a line-of-sight in an ionized region in order to absorb the photons effectively (if the covering factor is small, the condition that the mean recombination rate is equal to the mean photon emission rate implies that the clumps are mostly neutral, therefore not increasing the electron clumping factor). But if gas clumps with a high covering factor are responsible for the recombinations and, therefore, for the absorption of most photons before they reach the edge of the \( \text{HII} \) region and contribute to increase its size, then our estimate of the photoionization rate in the \( \text{HII} \) region is not valid because we assumed the mean-free-path of the ionizing photons to be \( L_i / 2 \), and it should now be reduced by the covering factor of the clumps. As long as the recombinations do not take place mostly at the edges of the \( \text{HII} \) regions (due to a higher gas density there), \( N_r \) cannot be larger than a few even for a very clumpy IGM. Notice that \( N_r \) is very large when \( z \gg 10 \), but of course the required size of an \( \text{HII} \) region \( L_i \) to allow for flux transmission between the two damping wings becomes more implausibly large as the redshift increases.

We therefore conclude that the optical depth \( \tau_i \) of an ionized region before reionization is complete should generally not be smaller than \( \sim 100 \). Rare exceptions to this are nevertheless allowed, because the photoionization rate inside the \( \text{HII} \) regions that we estimate above is only a mean value; for example, a line-of-sight may pass very close to a very luminous source. At the same time, the optical depth \( \tau_i \) is the value expected when the IGM density is equal to the mean baryonic density of the universe, but in reality a “\( \text{Ly}\alpha \) forest” should be caused by the IGM density fluctuations, just as observed at lower redshift. In photoionization equilibrium, the optical depth observed at a given wavelength is proportional to the square of the gas density. Therefore, the optical depth should be reduced by a factor of 100 in a void that is underdense by a factor of 10, allowing for some flux to be transmitted. The transmission of any flux when
$\tau_i$ is so large requires a void that is not only sufficiently underdense, but also sufficiently large to prevent the thermal broadening of the absorption due to the gas in adjacent structures, with typical overdensities near unity and temperature $\sim 10^4$ K, from overlapping and obstructing the window. For example, for absorbers with central optical depth $\sim 100$ and velocity dispersion $\sigma = 10$ Km s$^{-1}$ the thermal wings should extend to about $3\sigma$ on each side, requiring the void to have a diameter of at least $\sim (60$ Kms$^{-1})/H(z)$.

Possibly, the epoch of partial ionization in the IGM may be better observed in the Ly$\beta$ line (and higher order Lyman series), where the optical depth is reduced everywhere by a factor 0.16 relative to Ly$\alpha$. This could work in a source observed at a redshift close to the end of the reionization epoch, and if the intensity of the ionizing background rises quickly enough that, by the time the scale factor of the universe has increased by 1.18, significant flux is already being transmitted through the Ly$\alpha$ forest. But of course, contamination by the Ly$\alpha$ forest will make the analysis of the Ly$\beta$ spectrum very complex.

To summarize, the picture that emerges from this discussion is the following: at the redshift $z_n$ of the last neutral patch of the IGM on the line-of-sight from the source, a blue damping wing of absorption should be produced by the neutral gas. However, the ionized IGM at redshifts immediately below $z_n$ should normally have a large enough neutral fraction, in equilibrium with the ambient intensity of ionizing photons, to completely obstruct the flux from the source at the Ly$\alpha$ resonance, thus preventing the observation of the shape of the blue damping wing. The highest redshift at which transmitted flux will be seen should be that of a sufficiently underdense and large void, which can open up a “window” in the saturated absorption of the ionized IGM. Some of these voids might be located in the region where the optical depth of the blue damping wing is still significant, or even between two damping wings encircling an ionized region at $z > z_n$ with a size larger than $L_i$.

At $z < z_n$, the intensity of the ionizing background, $J_{HI}$, should rise as the mean-free-path of the photons increases, leading to an increase in the number of “windows” of transmitted flux associated with voids. The redshift evolution of these “windows” will provide information on the evolution of $J_{HI}$. How fast should the rise of $J_{HI}$ be? This depends on the rate at which the ionized material can recombine. In case I (where the mean rate of recombinations is much lower than the mean rate of emissions before the HII regions overlap), reionization occurs after one ionizing photon has been emitted for every proton in the IGM. At this point, the photon mean-free-path should rapidly increase by a large factor starting from the typical size of the HII regions, thereby causing a fast increase in the fraction of transmitted flux in Ly$\alpha$ spectra. The intensity of the background rises proportionally to $t - t_i$, where $t_i$ is the time at the end of reionization. The increased background radiation penetrates regions of denser gas, increasing the global rate of recombinations in the universe until they can balance the emission rate. This stops the linear growth of $J_{HI}$ with time, and the photon mean-free-path has grown to the mean separation along a random line-of-sight between the Lyman limit systems that have now been ionized, where enough recombinations take place to match the mean emission rate. The subsequent
evolution is known observationally: at $z \simeq 4$ to 5 the abundance of Lyman limit systems is still large enough to be the main factor limiting the intensity $J_{HI}$, and by $z \lesssim 2$ the mean-free-path has grown to the horizon scale, and $J_{HI}$ is limited mainly by the redshifting of photons.

On the other hand, in case II recombinations are already important before the HII regions start to overlap. At this time, the mean-free-path between Lyman limit systems associated with dense, self-shielded structures is about the same as the typical size of the HII regions. Thus, there is no sudden increase of the mean-free-path when the HII regions overlap. As the emission rate of photons increases and the universe expands, the self-shielded regions shrink in size and the newly ionized dense gas enables the global recombination rate to keep up with the emission rate, and this continues into the observed epoch at $z < 5$ as discussed previously. This leads to a much more gradual increase of the mean-free-path and of $J_{HI}$ compared to case I. Thus, the width of the redshift interval over which the Ly$\alpha$ forest increases its opacity, leading to the Gunn-Peterson trough, should give us information on the clumpiness in the IGM, which determines the rate of recombination at various stages of the reionization.

4. The He II Gunn-Peterson Trough

The first observations of absorption by He II at $\lambda = 304$Å have been performed over the last few years (Jakobsen et al. 1994; Tytler et al. 1995; Davidsen, Kriss, & Zheng 1996; Hogan, Anderson, & Rugers 1997; Reimers et al. 1997). The observation by Jakobsen et al. (1994) was consistent with a complete “Gunn-Peterson trough”, although the signal-to-noise that could be achieved allowed them only to place an upper limit to the mean transmitted flux of 20% of the total at $z \simeq 3.2$. The He II Ly$\alpha$ optical depth from a uniform IGM where all the helium is only once ionized is

$$\tau_{0,\text{He II}} = 2.3 \times 10^3 (\Omega_b h Y/0.01)[H_0(1+z)^{3/2}/H(z)][(1+z)/4]^{3/2}.$$  \hspace{1cm} (6)

Therefore, the observation of Jakobsen et al. could imply that the helium in the IGM was not yet doubly ionized, but it was also consistent with a typical He II fraction much smaller than unity (this remains true in a realistic model of an inhomogeneous IGM with on-going structure formation).

Davidsen et al. (1996) were the first to find evidence for the presence of transmitted flux to the blue of the He II Ly$\alpha$ line in another quasar, with a fraction $0.36 \pm 0.03$ over the redshift range $2.2 < z < 2.7$. The detection of flux immediately proves that the helium in the IGM was mostly twice ionized at $z < 2.7$, although it is possible that some patches of He II still remained at this epoch if the double reionization of helium was not yet complete. In fact, Reimers et al. (1997, hereafter R97) detected transmitted flux with much higher resolution in a second quasar, QSO HE 2347-4342, in the range $2.8 < z < 2.9$. All the transmitted flux appears in two windows, one at $\lambda = 1160$Å of width 4Å, and another at $\lambda = 1174$Å of width 2Å. The corresponding HI Ly$\alpha$ absorption spectrum (see Fig. 4 in R97) shows some weak absorption features in the
wider window, and no detectable absorption in the narrower. In particular, HI absorption at \( \lambda = 1159 \, \text{Å} \), in the middle of the wider HeII window, is clearly detected. On the other hand, there are other regions free of any detectable absorption in HI (e.g., at \( \lambda = 1171 \, \text{Å} \)) where the flux is completely absorbed in HeII. This demonstrates that the various regions in the IGM observed in this line-of-sight cannot all be photoionized by an ionizing background with approximately the same intensity, as shown in detail by R97 (see their Fig. 5). It is clear that, while in the two windows of the HeII spectrum the helium in the IGM must be mostly twice ionized, the other regions with low HI absorption must either have most of their helium only once ionized, or must have a much lower intensity of HeII ionizing photons.

The double ionization of helium could very well occur at a later epoch than the hydrogen ionization. If recombinations are not important during the reionization (case I as defined in the previous section), HeII will be ionized later if the ratio \( I_{\text{HeII}} / I_{\text{HI}} \) of emitted photons above the HeII ionization edge and above the HI ionization edge is lower than 0.08. But if many recombinations take place (case II), then we only need \( I_{\text{HeII}} / I_{\text{HI}} < 0.5 \), because HeII recombines 5.5 times faster than HI (Miralda-Escudé & Rees 1994). If quasars or starburst galaxies produce the ionizing background, then \( I_{\text{HeII}} / I_{\text{HI}} \lesssim 0.15 \) (Haardt & Madau 1996 and references therein). Since even in the absence of clumpiness, the HeII recombination time is equal to the Hubble time at \( z \approx 3 \), a delayed reionization of HeII relative to HI is clearly not just possible, but very likely.

This suggests that we could be observing the kind of patchy helium medium that we discussed previously for the case of hydrogen, and that the two windows of transmitted flux observed by R97 could be HeIII regions surrounded by HeII patches. However, the story for the HeII ionization is quite different from the case of hydrogen. The difference lies in the much larger thickness of the ionization fronts in the case of helium, due to the lower helium abundance by a factor 0.08, and the lower cross section of HeII by a factor 4. At \( z = 3 \) and in a region of density equal to the mean, a HeIII ionization front should have a proper thickness \( \sim 1 \, \text{Mpc} \), comparable to the largest HeIII regions that could be ionized by a single quasar. The corresponding velocity width is \( \sim 500 \, \text{Km s}^{-1} \) (much larger than the expected width of the damping wing for the HeII Gunn-Peterson trough, which is smaller than that of HI by a factor 0.08 at the same redshift).

The large thickness of the HeII ionization fronts implies that, during the epoch when the low-density IGM still contains a high fraction of HeII, it is not likely that any windows of transmitted flux can be seen through the HeII Gunn-Peterson absorption. In fact, if we repeat the analysis of the previous section to obtain the optical depth \( \tau_{i,\text{HeII}} \) of a HeIII region due to the HeII remaining in photoionization equilibrium, but this time expressing the answer in terms of the length of the HeIII region \( L_i = V_i / H(z) \), we obtain

\[
\tau_{i,\text{HeII}} = \frac{\tau_{0,\text{HeII}}}{N_r} \frac{750 \, \text{Km s}^{-1}}{V_i}.
\]

Since the windows of transmitted flux observed in R97 have velocity widths similar to \( V_i = 750 \, \text{Km s}^{-1} \), and \( N_r \) cannot be a large number due to the same arguments used in the last
section, we conclude that the optical depth in a HeIII region would in fact be close to $\tau_{0,\text{He\textsc{ii}}}$ (eq. 6) if the double reionization of helium was not yet complete. Another simple way to understand this result is that when the thickness of the ionization front is similar to the size of the HeIII regions, the fraction of HeII in the HeIII regions is not much less than unity.

The fact that the Davidsen et al. observations can be fitted with models where the helium is already doubly ionized at $z = 2.7$, with the expected shape of the spectrum for the ionizing background when quasars are the dominant sources (Miralda-Escudé et al. 1996, Croft et al. 1997) also suggests that the HeII reionization should be complete, and the state of the IGM should not be radically different at $z = 2.8$. The obvious differences in the HeII to HI column densities presented by R97 can be explained by large fluctuations in the intensity of the background above the HeII ionization edge, which are expected due to the large number of optically thick absorbers in HeII, but they do not demand a large HeII fraction in the regions free of HI absorption with no transmitted flux at HeII. As an example, consider a typical void in the IGM at $z \sim 3$ with a gas density a few times below average, where the hydrogen neutral fraction is $\sim 10^{-6}$. This yields an optical depth in the HI Ly$\alpha$ spectrum of $\sim 2\%$ (e.g., Croft et al. 1997), which would not be detected in any of the regions that are apparently free of absorption in the HI spectrum in Fig. 4 of R97 due to the uncertain continuum level. Given the mean spectrum of the ionizing background obtained from quasar models (Haardt & Madau 1996), with $J_{\text{HI}}/J_{\text{He\textsc{ii}}} \simeq 50$, the fraction of HeII in the same void should be $10^{-3}$, yielding a HeII Ly$\alpha$ optical depth of 0.4, which could perfectly well be the case for the two windows of flux in R97. But in another similar void where $J_{\text{HI}}/J_{\text{He\textsc{ii}}} = 500$ (due to absorption of the nearest quasars), the HeII optical depth should be 4 while the HeII fraction is still as low as $10^{-2}$.

5. Conclusions

In this paper we have attempted to predict the observable features that should be present in the spectrum of a high-redshift source seen behind a region of neutral IGM, still to be reionized.

The first feature is the damping wing of the Gunn-Peterson trough on the red side of the Ly$\alpha$ line. The width of the absorption profile of this damping wing provides a method to measure the density of the neutral IGM near the redshift of the source. There are two main difficulties for this measurement: the possibility of an absorption system large enough to contaminate the profile of the damping wing, and uncertainties in the intrinsic emission spectrum of the source. The second difficulty is particularly severe if the emitting source is a quasar, since quasars have strong, broad Ly$\alpha$ emission lines with profiles that are highly variable. The second feature we have discussed is the transition from the Gunn-Peterson trough to the Ly$\alpha$ forest. We have found that the Ly$\alpha$ forest should gradually become thicker with increasing redshift as the epoch of reionization is approached; at redshifts where the IGM was only partially ionized, the presence of any transmitted flux in individual cosmological H II regions surrounded by neutral patches of the IGM should be rare, due to the damping wings of the neutral zones and the very high Ly$\alpha$ optical
depth that is still caused by H II regions with the characteristic intensity of the ambient ionizing background that should be expected. It is also possible that some transmitted flux could be seen from H II regions in Lyβ, although that would of course be contaminated by the Lyα forest.

What type of sources can we expect to discover at ever higher redshifts in the future, to finally be able to probe the epoch of reionization? Quasars are the most luminous known sources, but there are signs that their abundance is declining at \( z \gtrsim 3 \) (Warren, Hewett, & Osmer 1994; Schmidt, Schneider, & Gunn 1995) and it is not clear if they can be found at much higher redshifts. Young galaxies must necessarily have existed when the IGM was partially ionized if they are the sources that caused the reionization, but the expectation is that they are hopelessly faint for obtaining good quality spectra (Haiman & Loeb 1997; MR97). Recently, a new class of luminous extragalactic sources in the ultraviolet has been identified: the afterglows of gamma-ray bursts (Costa et al. 1997a; van Paradijs et al. 1997). The afterglow was predicted from the cosmological fireball model (Mészáros & Rees 1997; Vietri 1997), and found to be in good agreement with observations (e.g., Wijers, Rees, & Mészáros 1997a; Waxman 1997). The third observation of an afterglow (Costa et al. 1997b; Djorgovski et al. 1997) resulted in the detection of an absorption system in the spectrum at \( z = 0.83 \) (Metzger et al. 1997), which has definitely put to rest any doubts on the cosmological nature of GRBs. The optical magnitudes of the GRB afterglows are similar to the luminous high-redshift quasars. It is quite plausible that these afterglows will be found in the coming years at redshifts higher than any other known sources; in fact, if GRBs are produced in objects belonging to young stellar populations, then they should take place soon after the first stars were formed in the universe (Wijers et al. 1997b). At very high redshifts, the probability of gravitational lensing is high, and this can help in boosting the apparent brightness of some GRBs and their afterglows. The very important advantage of GRB afterglows is that their intrinsic spectrum is supposed to be a featureless power-law on small wavelength ranges, because the radiation originates from synchrotron emission in a relativistic shock. This eliminates the severe systematic error of measuring the absorption profile of a damping wing near an emission line in the case of a quasar. Thus, unless gamma-ray bursts did not take place for some reason until a much later time than the epoch when the first stars (or the first sources that caused the reionization) formed, their afterglows should become a precious tool to study the IGM at very high redshift.

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Appendix

We calculate here the accurate profile of the damping wing of the Gunn-Peterson trough caused by a homogeneous neutral IGM. The scattering cross section of the Lyα resonance line by neutral hydrogen is given by (see Peebles 1993, §23)

\[
\sigma(\omega) = \frac{3\lambda_\alpha^2 \Lambda^2}{8\pi} \frac{(\omega/\omega_\alpha)^4}{(\omega - \omega_\alpha)^2 + (\Lambda^2/4)(\omega/\omega_\alpha)^6} .
\]

The notation is the same as that used in §2, and \(\omega_\alpha = 2\pi \nu_\alpha = 2\pi c/\lambda_\alpha\). The second term in the denominator can be neglected, because we are only interested in the shape of the damped profile far from the center of the line (i.e., when \(\parallel \omega - \omega_\alpha \parallel \gg \Lambda\), where the resulting optical depth is not very large. The term in the numerator causes the classical Rayleigh scattering, and was neglected in §2 assuming \(\parallel \omega - \omega_\alpha \parallel \ll \omega_\alpha\), but this is a poor approximation since the damping wing can be quite broad, and we keep this term here. We assume that the IGM has a constant neutral hydrogen comoving density \(n_0\) at redshifts \(z_n < z < z_s\), where \(z_s\) is the redshift of the source, and the density is negligibly small at \(z < z_n\). The optical depth observed at a wavelength \(\lambda = \lambda_\alpha(1 + z_n) + \Delta \lambda\) is

\[
\tau(\Delta \lambda) = \int_{z_n}^{z_s} \frac{dz}{1 + z} \frac{c}{H(z)} n_0(1 + z)^3 \sigma \left( \frac{\omega}{\omega_\alpha} = \frac{(1 + z)}{(1 + z_s)(1 + \delta)} \right),
\]

where \(\delta \equiv \Delta \lambda/\lambda_\alpha(1 + z_n)\). The Gunn-Peterson optical depth outside the damping wing is \(\tau_0(z_s) = 3\lambda_\alpha^2 \Lambda n_0/[8\pi c H(z_s)]\), and using \(H(z) \propto (1 + z)^3/2\), we obtain:

\[
\tau(\Delta \lambda) = \frac{\tau_0 R_\alpha}{\pi} \int_{z_n}^{z_s} \frac{dz}{1 + z} \left( \frac{1 + z}{1 + z_s} \right)^{11/2} (1 + \delta)^{-4} \left[ \frac{1 + z}{(1 + z_s)(1 + \delta) - 1} \right]^{-2} .
\]

This reduces to:

\[
\tau(\Delta \lambda) = \frac{\tau_0 R_\alpha}{\pi} (1 + \delta)^{3/2} \int_{x_1}^{x_2} \frac{dx x^{9/2}}{(1 - x)^2} ,
\]

where \(x_1 = (1 + z_n)/[(1 + z_s)(1 + \delta)]\), \(x_2 = (1 + \delta)^{-1}\), and the result of the integral is

\[
\int \frac{dx x^{9/2}}{(1 - x)^2} = \frac{x^{9/2}}{1 - x} + \frac{9}{7} x^{7/2} + \frac{9}{5} x^{5/2} + 3 x^{3/2} + 9 x^{1/2} - \frac{9}{2} \log \frac{1 + x^{1/2}}{1 - x^{1/2}} .
\]
REFERENCES


Costa, E., et al. 1997b, IAU Circ 6649


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Fig. 1.— Absorption profile of the damping wing of the Gunn-Peterson trough, predicted using the equation given in the Appendix. The fraction of transmitted flux is shown as a function of the wavelength interval $\Delta \lambda$ from the Ly$\alpha$ wavelength of the source, $\lambda_{\alpha}(1 + z_s)$. The solid line assumes the parameters $z_s = 9$, $\tau_0 = 4.3 \times 10^5$, and $z_n = 7$ (where the IGM is assumed to have a constant neutral density at $z_n < z < z_s$, and be fully ionized at $z < z_n$). The dotted line is the case where an absorption system with $N_{HI} = 2 \times 10^{20} \text{ cm}^{-2}$ is present at $z_s = 9$, which could be due to a galaxy where the source is located. The dashed line shows the damping wing profile without any additional absorption system, but with the parameters changed to $z_s = 9.009$ (although $\Delta \lambda$ is still defined as the wavelength interval from the Ly$\alpha$ line at $z = 9$), $\tau_0 = 4.9 \times 10^5$, and provides the best fit to the dotted line assuming there is no absorption system at the source redshift. This illustrates the difficulty in measuring $\tau_0$ in the presence of an absorption system.