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Probing the End of the Dark Age: Quasar Strömgren Spheres Before Cosmological Reionization

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Abstract. During the initial phase of the cosmological reionization epoch, the ionizing sources embedded in the neutral intergalactic medium (IGM) generate discrete HII regions. We show that a sufficiently bright quasar (for example, one tenth as luminous as the quasar recently discovered at redshift $z = 5.8$ by Fan et al.) can ionize a large volume, allowing the transmission of a substantial fraction of the flux of its intrinsic Lyα emission line on both sides of the Lyα wavelength. The observed line profile is richly informative. We show that a sufficiently accurate, high spectral resolution ($R \approx 10^4$) measurement of the line profile of a bright quasar is feasible using the *Next Generation Space Telescope (NGST)* as well as large ground-based telescopes. Such a measurement has two potentially important applications. First, the red side of the Lyα emission line provides a way to measure the quasar lifetime. Second, the blue side provides a direct measure of the clumping factor of the intergalactic medium at the quasar redshift. The estimate of the absorption of the red side is limited by the accuracy to which the intrinsic profile of the Lyα emission line is known. The blue side, however, does not sensitively depend on the intrinsic profile, because the former is much narrower than the latter.

1. Introduction

The epoch of cosmological reionization, and the nature of the ionizing sources bear fundamental cosmological importance, but are yet unknown. In contrast, we have a better understanding of how the reionization might have happened: individual HII regions, whether around galaxies or quasars (or sources of other nature), start out as isolated islands, eventually overlap to fill the universe and complete the reionization process (Aaron & Wingert 1972; Shapiro & Giroux 1987; Gnedin & Ostriker 1997; Haiman & Loeb 1998; Miralda-Escudé et al. 1999). In this *Letter* we suggest that it may be possible to directly probe the structure of an HII region around a bright quasar before the reionization is complete. Although we do not necessarily have to identify the primary reionization sources with quasars, the existence of bright quasars at high redshift is sup-

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ported by the recent discovery of the very bright quasar at $z = 5.8$ in the Sloan Digital Sky Survey (SDSS; Fan et al. 2000; hereafter F00).

To study the size and structure of an individual Strömgren sphere, we propose to utilize the observed profile of the quasar's Lyα emission line. When a source is embedded in a neutral IGM, its emission line suffers from strong absorption by the damping wing of the resonance Lyα absorption of the intervening neutral IGM (Miralda-Escudé 1998). As a result, the Lyα photons are absorbed and re–emitted multiple times in the IGM, resulting in an extended, low–surface brightness line, which is difficult to observe (Loeb & Rybicki 1999). In contrast, if the source is surrounded by a large HII region, the Lyα photons can escape absorption, provided they redshift out of resonance before they reach the boundary of the HII region. In this *Letter*, we show that a sufficiently bright quasar placed at $z \geq 6$ can produce a sufficiently large Strömgren sphere to render its Lyα emission line detectable, using the *Next Generation Space Telescope (NGST)*, as well as high spectral resolution ground based telescopes such as Keck and the Hobby-Eberly (HET) telescopes. Conclusions similar to those in the present study were reached independently by Madau & Rees (2000), who emphasize that the observability of the Lyα line therefore does not directly imply a constraint on the reionization redshift. Throughout this *Letter*, we adopt a flat ΛCDM background cosmology dominated by a cosmological constant and cold dark matter, with density parameters $(\Omega_\Lambda, \Omega_0, \Omega_{\rm b}) = (0.7, 0.26, 0.04)$, and Hubble constant $H_0 = 70$ km s^{-1}.

2. Strömgren Spheres Around Quasars

According to its classical definition in stellar astronomy, a Strömgren sphere is an HII region around an individual, ionizing-photon-emitting O/B star, within which the rate of recombinations exactly balances the emission rate $\dot{N}_{ph}$ of ionizing photons from the star. The radius R_s of the Strömgren sphere is given by

$$R_s = \left[\frac{3\dot{N}_{ph}}{4\pi\alpha_B\langle n_H^2\rangle}\right]^{1/3}, \qquad (1)$$

where α_B is the hydrogen recombination coefficient evaluated at $\approx 10^4$K, and $\langle n_H^2\rangle$ is the mean squared hydrogen density within R_s.

An analogous situation arises on much larger scales, for cosmological ionizing sources such as galaxies and quasars (Shapiro & Giroux 1987). There are, however, several important differences between the stellar case and the cosmological situation. The most important one for our purposes is that the hydrogen recombination time in the IGM is longer than the Hubble time at the relevant epochs ($z \lesssim 10$), which in turn must be longer than the lifetime of the quasar. As a result, the size R_s of the *equilibrium* Strömgren sphere is large, but is never reached in practice before the ionizing source turns off. If recombinations are negligible, then the radius R_{t_Q} of the ionized region around a steady source of age t_Q would simply be

$$R_{t_Q} = \left[\frac{3\dot{N}_{ph}t_Q}{4\pi\langle n_H\rangle}\right]^{1/3}, \qquad (2)$$

where $\langle n_H \rangle$ is the mean hydrogen density within R_{t_Q}. A second difference is that in the stellar case, the Strömgren sphere is static if the luminosity of the source is constant, whereas in the quasar case the sphere around a long–lived quasar can evolve due to the evolution of density around a quasar (both mean density and clumping factor) as well as the accumulation of ionizing photons (equation 2 and equation 4 below), even if the source luminosity remains constant. To fully take the above effects into account, one needs to solve the equation of motion for the ionization front, R_i,

$$\frac{dR_i^3}{dt} = 3H(z)R_i^3 + \frac{3\dot{N}_{ph}}{4\pi\langle n_H \rangle} - C_{\rm HII}\langle n_H \rangle \alpha_B R_i^3, \quad (3)$$

where $H(z)$ is the Hubble constant at z, and $C_{\rm HII} \equiv \langle n_H^2 \rangle / \langle n_H \rangle^2$ is the mean clumping factor of ionized gas within R_i. The first term in equation 3 accounts for the Hubble expansion, the second term accounts for the ionizations by newly produced photons, and the last term describes recombinations (Shapiro & Giroux 1987; Haiman & Loeb 1997). In practice, we find that the apparent size of a quasar Strömgren sphere is primarily determined by the total number of ionizing photons emitted. Assuming that the quasar luminosity $\dot{N}_{ph}$ is constant, the solution of equation 3 is accurately described by R_{t_Q} given in eq. 2. Gas clumping is unlikely to significantly change this answer. As a specific example, with the ionizing photon emissivity of the SDSS quasar, and for $C_{\rm HII} = 100$, we find that R_i would be reduced by 10% at $\approx 10^7$ yr, and by 50% at $\approx 10^8$ yr. Cosmological simulations indicate that the value of $C_{\rm HII}$ is likely to be significantly below 100 (Gnedin & Ostriker 1997).

3. Lyα Transfer Across a Strömgren Sphere

The main purpose of this *Letter* is to assess the effect of the quasar's HII region on the observed profile of its Lyα line. Consider a source located at $z_s \gtrsim 6$ before reionization is complete, whose age is t_Q. The source is assumed to be surrounded by a spherical HII region of size $R_i(t_Q)$, but is otherwise embedded in a neutral IGM. The source is also assumed to emit a Lyα emission line, which is subsequently reprocessed by the opacity of the intervening neutral IGM, as well as of the residual neutral hydrogen within the HII region itself.

The optical depth between the source and the observer at $z = 0$, at the observed wavelength $\lambda_{\rm obs} = \lambda_s(1 + z_s)$, is given by

$$\tau(\lambda_{\rm obs}, z_s) = \int_{z_r}^{z_s} dz c \frac{dt}{dz} n_H(z) \sigma_\alpha[\lambda_{\rm obs}/(1+z)], \quad (4)$$

where cdt/dz is the line element in the assumed ΛCDM cosmology, n_H is the neutral hydrogen density, and σ_α is the Lyα absorption cross–section. The reionization redshift is assumed conservatively to be $z_r = 6$, but the precise value (as well as the details of the reionization process) is irrelevant here, since we are only sensitive to the optical depth near the source redshift z_s, where the IGM is assumed to be still fully neutral. It is useful to divide the range of integration in equation 4 into two parts, to reflect the contributions to the optical depth from within ($z_i < z < z_s$) and outside ($z_r < z < z_i$) the HII region, where z_i is the redshift somewhat below z_s, corresponding to the boundary of the HII region ($z_i \approx z_s - R_i[t]/R_H[z_s]$, where $R_H[z_s]$ is the size of the cosmological horizon at z_s).

The Lyα absorption cross–section is assumed to be described by a numerically computed Voigt profile (see eq. 6 of Press & Rybicki 1993). The gas temperature for this profile is taken to be $T = 10^4$K within the HII region, and $T = 1.2[(1+z)/8]^{-2}$ K outside it.[1] Outside the HII region, the neutral hydrogen density is assumed to follow the IGM density, $8.5\times10^{-5}[(1+z)/8]^3$ cm^{-3}. Inside the HII region, the neutral hydrogen density depends on the ionized fraction. Assuming photoionization equilibrium (justified for the source lifetimes of $> 10^6$ yr considered here), and that the gas is highly ionized, the neutral hydrogen fraction $x = n_{HI}/n_H \ll 1$ at the radius r away from the source is given by

$$\alpha_B C_{\rm HII}\langle n_H\rangle = x\int_{\nu_H}^{\infty} d\nu \frac{L_\nu}{4\pi r^2}\frac{\sigma_\nu}{h\nu} = \frac{x\bar\sigma \dot N_{ph}}{4\pi r^2}. \tag{5}$$

Here L_ν is the intrinsic luminosity of the source in erg s^{-1} Hz^{-1}, ν_H and σ_ν are the ionization threshold and cross section of hydrogen, and we have defined the luminosity weighted cross section

$$\bar\sigma \equiv \int_{\nu_H}^{\infty} d\nu \frac{L_\nu \sigma_\nu}{h\nu} \times \left[\int_{\nu_H}^{\infty} d\nu \frac{L_\nu}{h\nu}\right]^{-1}, \tag{6}$$

whose value is $\bar\sigma = 2.5\times10^{-18}$ cm^2 for the Elvis et al. (1994) template spectrum (the same value would be obtained for a power law spectrum with a slope of $\nu^{-1.8}$). The resulting neutral hydrogen fraction is

$$x = 10^{-6} C_{\rm HII}\left(\frac{r}{1\ {\rm Mpc}}\right)^2 \left(\frac{\dot N_{ph}}{10^{57}\ {\rm s}^{-1}}\right)^{-1}\left(\frac{1+z}{8}\right)^3. \tag{7}$$

This equation applies within the optically thin central region of the Strömgren sphere where $x \ll 1$, and shows that for bright sources of interest here, this region is highly ionized. Near the boundary of the HII region, the neutral fraction rapidly increases to unity, where the $x \ll 1$ condition breaks down and equation 7 becomes invalid. However, this does not affect the results shown below for the following reasons. First, the flux transmission shortward of the Lyα wavelength that we are concerned with occurs in regions with optical depth $\tau \leq 7$ or $x \leq 5\times10^{-5}$. Second, the optical depth longward of the Lyα wavelength is roughly $0.5x(\Delta\lambda/100\mathring{A})^{-1}$ for the cosmological parameters adopted here (Miralda-Escudé 1998), and is dominated by neutral ($x = 1$) IGM outside the Strömgren sphere. Therefore for most of the transmitted flux on both sides, the boundary region of the Strömgren sphere does not enter. We assume that the jump from $x(R_i)$ to unity takes place as a step function at the radius $R_i(t_Q)$.

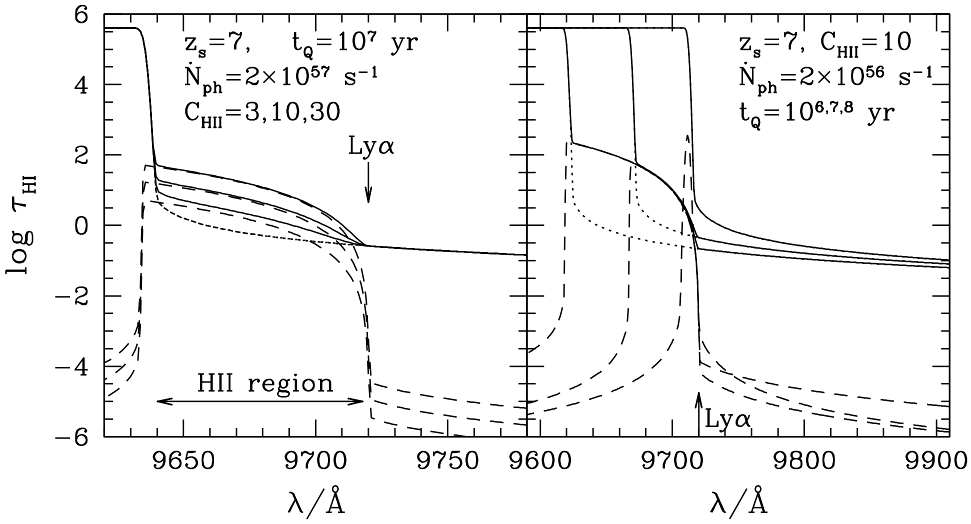

Figure 1. The total line optical depth (solid curves) towards a quasar at $z_s = 7$, as a function of observed wavelength. Also shown are the separate contributions from the neutral IGM (dotted curves) and from the residual neutral hydrogen within the HII region (dashed curves). The left panel demonstrates the effect of different clumping factors ($C_{\rm HII} = 3, 10, 30$); the right panel demonstrates the effect of different quasar lifetimes ($10^6, 10^7, 10^8$yr).

4. Results and Discussion

Fig. 1 shows the optical depth around the Lyα line for a quasar at $z_s = 7$. The left panel shows that, for a bright quasar like that of F00, the optical depth longward of the Lyα wavelength is nearly independent of the clumping factor, simply because the optical depth in that region is dominated by the damping wing of the neutral IGM (dotted curves in the left panel) outside the Strömgren sphere, whose radius is insensitive to $C_{\rm HII}$ as long as $C_{\rm HII} \leq 100$ (see §2). The situation is dramatically different for a fainter quasar as shown in the right panel of Fig. 1; because the HII region is much smaller, the red damping wing produced by the neutral IGM outside the Strömgren sphere start to reflect the size of the sphere hence the age of the quasar. The dependence of the red damping wing on the clumping factor is very weak, because the contribution from the residual neutral hydrogen within the Strömgren sphere is small. On the other hand, the optical depth shortward of the Lyα wavelength within the stretch of the Strömgren sphere is always dominated by the residual neutral hydrogen inside the Strömgren sphere (dashed curves), and therefore is proportional to $C_{\rm HII}$ (equation 7), in sharp contrast with the situation at the longward of the Lyα wavelength. However, the optical depth shortward of the Lyα wavelength it is quite insensitive to t_Q (equation 7).

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[1]The latter value assumes that the IGM temperature is coupled to the cosmic microwave background untul $z = 150$, and cools adiabatically thereafter.

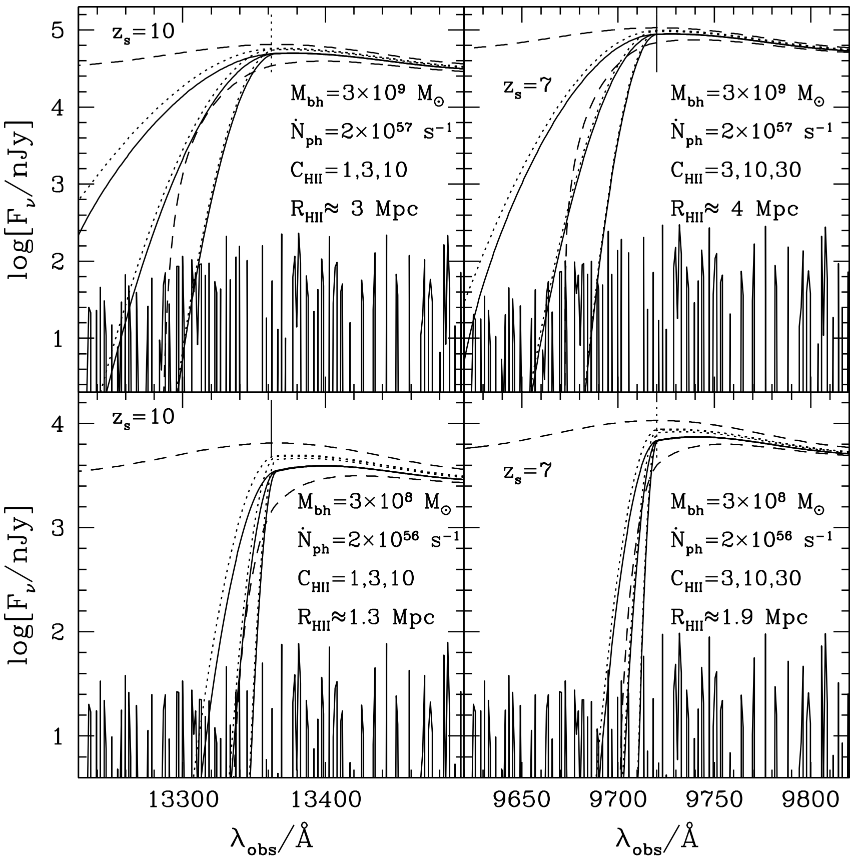

Figure 2. The transmitted line profile for the Lyα line of quasars with a black hole masses of $2 \times 10^{8,9}$ $M_{\odot}$ at redshifts of $z_s = 7, 10$. The three solid curves show the transmission for a quasar lifetime $t_Q = 10^7$ yr, and clumping factors of $C_{\rm HII} = 1, 3, 10$ ($z = 10$) or $C_{\rm HII} = 3, 10, 30$ ($z = 7$) (top to bottom), relative to the unabsorbed profile (upper dashed curves), and expected *NGST* noise. The dotted lines show the same for $t_Q = 10^8$ yr. The lower dashed curve assumes $t_Q = 10^6$ yr, and $C_{\rm HII} = 1$ at $z = 10$ and $C_{\rm HII} = 1$ at $z = 7$.

Let us now translate the theoretical illustration in Fig. 1 to observable spectra of quasars around the Lyα emission line shown in Fig. 2. A logarithmic ordinate is used to better show the flux over many orders of magnitude down to the expected noise level (although the spectral line may appear misleadingly flat). We adopt the black hole (BH) mass and luminosity inferred from the quasar at $z = 5.8$ observed by F00 and place it either at $z_s = 10$ or $z_s = 7$ in the top two panels; another quasar with one tenth of this luminosity is used for the two bottom panels. In all cases, the profile of the Lyα emission line is assumed to be Gaussian with a half-width of $1,500$ km/s, and with a central flux that is twice the continuum. The random noise shown at the bottom of each panel in

Fig. 2 is estimated assuming a 10^5 second integration with the *NGST* (see http://augusta.stsci.edu for details on the expected backgrounds) with a spectral resolution of R=10,000. Obviously, it is advantageous to use high resolution spectroscopy to maximize the number of pixels that probe the structure of the HII region on the blue side of the emission line (especially for faint and/or very young quasars). At spectral resolutions this high, the dominant noise is either the Poisson photon noise (for bright sources with $\dot{N}_{ph} \gtrsim 10^{56}\ \mathrm{s}^{-1}$) or the detector noise (for fainter sources), rather than the zodiacal light or sky background, implying that a ground based telescope such Keck or HET with sufficient spectral resolution should work just as well as *NGST*.

A rich amount of information is contained in the profile of the line. We see that the red side of the Lyα emission line is largely transmitted even for the fainter quasar adopted at the bottom panels, consistent with Fig. 1 showing an optical depth of ~ 0.1 there (except near the Lyα wavelength for the case with $t_Q = 10^6$ yr, where the radius of theStrömgren sphere is sufficiently small that the damping wing of the neutral IGM contributes an optical depth significantly above unity.) For the brighter quasar shown in the top panels the transmission on the red side is insensitive to either t_Q or $C_{\rm HII}$, whereas for the fainter quasar shown in the bottown panels the transmission on the red side is sensitive to t_Q but not to $C_{\rm HII}$. It is therefore possible to measure the lifetime of a relatively faint quasar (perhaps the majority of the quasars belong to this category) before reionization is complete. The primary uncertain factor is the intrinsic Lyα emission profile.

The blue side of the Lyα emission line is not completely absorbed. On the contrary, we see in the top panels of Fig. 2 that for a quasar observed by F00 with $t_Q > 10^7$ yr there is a large range $\Delta\lambda \approx 50 - 150$Å where the flux is at least ten times above the noise (S/N=10). Even if the quasar is ten times fainter, one should still be able to detect of order several tens of spectral pixels if $t_Q > 10^6$ yr (assuming $R = 10^4$). More interestingly, the extent of the flux transmission on the blue side is a strong function of $C_{\rm HII}$ [$\propto \exp(-\beta C_{\rm HII})$, where β is a known constant of order $0.1 - 1.0$] but a very weak function of t_Q. This provides a potentially powerful tool to probe the clumping factor at high redshift; i.e., it directly measures the small scale power at high redshift, since the clumping is chiefly contributed by small scale fluctuations. Since the intrinsic Lyα emission of a quasar is expected to be significantly broader than the width of the blue side of the absorbed spectrum, the latter should not sensitively depend on the exact intrinsic width of the unabsorbed Lyα emission line. In any case, the red side of the profile traces the intrinsic profile well for a bright quasar. It is therefore possible that fitting the entire observed profile significantly removes the uncertainty of the unknown intrinsic profile, as long as it is reasonably symmetric and sufficiently broad.

5. Conclusions

A quasar one tenth as luminous as that recently reported by F00, if placed in the neutral IGM at $z_s \geq 7$ before cosmological reionization, generates a large HII island (a Strömgren sphere). We show that for such a quasar a substantial fraction of the flux at both the blue and red sides of the Lyα emission wavelength can be transmitted. For the range of wavelengths around the Lyα wavelength where significant transmission of flux occurs, the red damping wing of the neutral IGM outside the Strömgren sphere dominates the optical depth longward of the Lyα wavelength, whereas the residual neutral hydrogen inside the (highly ionized) Strömgren sphere dominates the optical depth shortward of the Lyα wavelength. While the flux longward of the Lyα wavelength is not substantially suppressed to a large offset in wavelength ($\delta\lambda \geq 100$A), the blue side of the Lyα emission line is more absorbed than the red side and displays a distinct profile that drops sharply with decreasing wavelength. Nevertheless, the flux at the blue side is clearly detectable even for a quasar 10 times fainter than that found by F00. We show that *NGST* as well as large ground-based, high spectral resolution telescopes with a spectral resolution of $R = 10^4$ should be able to provide such a detection.

Two important applications of such a partially absorbed Lyα emission line are suggested. First, for a relatively faint quasar (for example, one tenth as luminous as that found by F00), the red side of the Lyα line profile depends mostly on the age of the quasar and therefore can be used to infer it. The main uncertainty is the unknown intrinsic profile. Second, for bright quasars, the blue side of the Lyα line profile is also detectable, and depends only very weakly on the lifetime of a quasar but very strongly on the clumping factor of the medium around the quasar. Therefore, one can use it to directly measure the fluctuation of gas on small scales at high redshift. This may provide a unique opportunity to probe the small-scale power at very high redshift, where competing cosmological models differ most.

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