The proximity effect around high redshift quasars

Simona Gallerani

INAF - Osservatorio Astronomico di Roma, Via Frascati 33, 00040 Monteporzio (RM).

The term proximity effect refers to the relative lack of Lyα absorption in quasar spectra close to the ionizing source, produced by the enhanced photoionization rate due to the local radiation field. This effect can be detected both by looking along the line of sight of the quasar, (proximity effect along the line of sight) and also by studying the effect produced in the Lyα forest of a bright quasar by a foreground source located close to the quasar line of sight (transverse proximity effect). The proximity effect has been appreciated as a tool to investigate on the ionization level of the Universe at redshifts approaching the reionization epoch, and to study the environment and properties of quasars. In this work we discuss the limits related to the use of the proximity effect along the lines of sight towards high-z quasars to measure the neutral hydrogen fraction at \( z \approx 6 \). Moreover, we present the first-ever detection of the transverse proximity effect in the HI Lyα forest.

I. INTRODUCTION

The sudden rise of the Gunn-Peterson optical depth (\( \tau_{\text{GP}} \)) detected in quasar absorption spectra at \( z \approx 6 \), along with the appearance of very large portions of completely absorbed flux\(^1\), have been interpreted as an evidence for the complete reionization of the universe to occur at \( z \approx 6 \) (Fan et al. 2006). However, constraints on the intergalactic medium (IGM) ionization state derived by using Lyα forest spectroscopy must take into account the extremely high sensitivity of \( \tau_{\text{GP}} \) to tiny neutral hydrogen amounts. Indeed, a volume averaged neutral hydrogen fraction as low as \( x_{\text{HI}} \approx 10^{-3} \) (Fan et al. 2002) is sufficient to completely depress the transmitted flux in quasar absorption spectra. For this reason, recently, many studies have tried to clarify if the SDSS data effectively require that the IGM was reionized as late as \( z \approx 6 \), finding that indeed quasar observational data currently available are compatible with a highly ionized Universe at these epochs (e.g. Gallerani et al. 2006; Becker et al. 2007).

Alternatively, several authors have tried to constrain \( x_{\text{HI}} \) at high redshift by analyzing the proximity effect along the line of sight of high-z quasars (e.g. Mesinger & Haiman 2004, Bolton & Haimelt 2006). As a consequence of the enhanced photoionization rate due to the local radiation field an ionized bubble (generally called “HII region”) is formed around the source. Although at \( z \approx 6 \) the neutral hydrogen fraction become high enough to produce large gaps in quasar spectra, the presence of the HII regions around high-z quasars could let the emitted photons to be shifted out of the resonance Lyα core. Thus, they can freely travel without being absorbed towards the observer. As a consequence, in the region blue-ward the Lyα emission line a region of transmitted flux does appear. The size of this transmissivity window can be identified as the HII region extent and used to constrain the IGM ionization state.

The evolution of the HII region radius \( R_d \) is given by the following relation:

\[
\frac{dR_d}{dt} = c \frac{\dot{N}_\gamma - \frac{4}{3} \pi R_d^3 \alpha_{\text{HII}} n_H^2}{N_\gamma + 4 \pi R_d^2 x_{\text{HI}} n_H c - \frac{4}{3} \pi R_d^3 \alpha_{\text{HII}} n_H^2},
\]

where \( \dot{N}_\gamma \) is the number of ionizing photons emitted by the monochromatic source per unit time, \( n_H \) is the number density of hydrogen atoms, and \( \alpha_{\text{HII}} \) is the recombination coefficient for ionized hydrogen. This expression explicitly takes into account the time delay for a photon to travel from the source to the edge of the HII region, thus setting the limiting expansion speed of the HII region to the speed of light.

Any photons instantaneously detected by the observer were emitted at the same retarded time, \( t_R = t - R_d / c \), where \( t \) is the time when the photons reach a distance \( R_d \) from the source. Evaluating Eq. 1 at the retarded time yields

\[ dh \]
\[ \frac{dR_d}{dR} = \frac{\dot{N}_\gamma - \frac{4}{3}\pi R_d^3 \alpha_{\text{HI}} n_{\text{HI}}^2}{4\pi R_d^2 n_{\text{HI}}} . \quad (2) \]

Moreover, the recombination timescale \( t_{\text{rec}} = (\alpha_{\text{HI}} n_{\text{HI}})^{-1} \), at \( z \approx 6 \), is much larger than typical quasar lifetime \( t_Q \approx 10^7 \). Thus, recombinations can be neglected and Eq. (2) reduces to:

\[ R_d = \left( \frac{3}{4\pi} \frac{\dot{N}_\gamma t_Q}{n_{\text{HI}}} \right)^{1/3} . \quad (3) \]

From Eq. (3) it is clear that, if the intrinsic properties (\( \dot{N}_\gamma, t_Q \)) of the quasar are known, the extension of the HII region measures the neutrality of the IGM.

Wyithe et al. (2005), and Wyithe & Loeb (2006) have applied for first this method to 7 quasars at \( z > 6 \). According to their arguments, the small sizes of the HII regions (\( \approx 10 \) physical Mpc) imply that the typical neutral hydrogen fraction of the IGM beyond \( z \approx 6 \) is in the range 0.1 to 1. In the second section of this paper we discuss the limits related to the use of the proximity effect along the lines of sight towards high-\( z \) quasars to measure the neutral hydrogen fraction at \( z \approx 6 \).

The proximity effect has been appreciated also as a tool to investigate the intrinsic properties of the quasar responsible of the HII region. This is possible by looking, not only along the line of sight of the quasar affecting the surrounding IGM, but also at the effect produced in the Ly\( \alpha \) forest of the background quasar by a foreground source located close to the quasar line of sight (LOS). This is usually referred to as the transverse proximity effect. The transverse proximity effect is expected to induce a decrease in strength of the absorption in the Ly\( \alpha \) forest (of the background quasar) at the redshift of the foreground quasar. Searches for the transverse proximity effect in the HI Ly\( \alpha \) forest at \( z \approx 6 \) have been so far unsuccessful. Such effect has been detected only by HeII absorption studies (Worseck & Wisotzki 2006; Worseck et al. 2007). In the third section of this paper we present the first-ever detection of the transverse proximity effect in the HI Ly\( \alpha \) forest. We summarize our conclusions in the last section.

**II. PROXIMITY EFFECT ALONG THE LINE OF SIGHT**

Maselli et al. (2007) have performed a combination of multiphase Smoothed Particle Hydrodynamics (SPH, Springel & Hernquist 2003) and 3D Radiative Transfer simulations (CRASH, Maselli et al. 2005) in order to predict reliably the geometrical shape of the HII region around a typical quasar observed at \( z \gtrsim 6 \). High-\( z \) luminous quasars reside in rare overdense regions where the IGM physical properties are highly biased (Yu & Lu 2005). This bias has been taken into account by using a snapshot centered at \( z_Q = 6 \) of the G5 simulation described in Springel & Hernquist (2003). With its large computational volume (100 h\(^{-1}\) comoving Mpc on a side) and a particle resolution of \( 2 \times 324^3 \), G5 allows to properly follow the quasar HII region volume at a sufficiently high resolution. The density field is centered on the most massive halo, \( M_{\text{halo}} \approx 2.9 \times 10^{12} \text{M}_\odot \). This mass is consistent with that expected for halos hosting high-\( z \) luminous quasars (Wyithe & Loeb, 2006).

The SPH density field has been mapped on a Cartesian grid with 128\(^3\) cells, in order to perform full 3D RT simulations. The quasar is embedded in the most massive halo and a Telfer
template (Telfer et al. 2002) in the energy range 13.6eV – 42eV has been adopted for the quasar UV spectrum. Furthermore, the following values are assumed for the quasar intrinsic properties: \( t_0 = 10^7 \) yr and \( N_e = 5.2 \times 10^{56} \) s\(^{-1}\).

Initially, the IGM is in photoionization equilibrium with an uniform ionizing background (produced by sources other than the considered quasar) with a mean photoionization rate \( \Gamma_{12} = 0.015 \) s\(^{-1}\), yielding \( \langle x_{HI} \rangle = 0.1 \). This value corresponds to the lower limit found by previous works (Mesinger & Haiman 2004; Wyithe & Loeb 2006). Figure 2 shows the \( x_{HI} \) distribution across the quasar location at \( t = t_0 \), the end of the RT simulation. The HII region does not exhibit strong deviations from spherical symmetry. This result is not unexpected: the radiative energy density inside the HII region during the early phases of the evolution is so large that clumps possibly responsible for flux anisotropies are completely ionized and made transparent. RT effects are instead apparent in the jagged ionization front (IF), causing the size of the HII region to fluctuate along different LOS. We define the radius of the HII region, \( R_d \), along a given LOS as the distance from the quasar at which \( x_{HI} > 10^{-3} \), marking the IF. The RT-induced scatter in the radius of the HII region is seen in Figure 2 via the probability distribution function (PDF) of \( R_d \) resulting from a sample of 1000 LOS piercing the box through the quasar position. The mean value, \( \langle R_d \rangle = 6.29 \pm 0.37 \) (1-\( \sigma \)), matches quite well the one derived from the analytical formula (Eq. 3) mentioned in the Introduction.

Next, we derived 1000 mock quasar absorption spectra along the same set of LOS used for \( R_d \). The details of the adopted technique are given in Gallerani et al. (2006); in brief, each spectrum is characterized by a spectral resolution \( R = \lambda / \Delta \lambda \approx 8000 \). To enable comparison with data each spectrum has been smoothed to \( R = 4500 \) and Gaussian noise has been added, yielding a signal-to-noise ratio \( S/N = 50 \).

From these spectra one can derive the observed HII region radius, \( R_f \), identified by the redshift at which the transmitted flux is \( > 0.1 \), when the spectrum is rebinned to \( \Delta \lambda = 20 \) Å (Fan et al. 2006). The \( R_f \) PDF obtained is shown in Figure 2 (top panel). From the Figure a large offset between \( \langle R_d \rangle = 6.29 \) Mpc and \( \langle R_f \rangle = 4.25 \) Mpc is seen: i.e. the size of the HII region extracted from the spectra is systematically underestimated. We refer to this effect as apparent shrinking. Also shown in Figure 2 (middle panel) are the template and absorbed spectra, along with the \( n_{HI} \) density distribution as a function of observed wavelength, for a representative LOS. The total GP optical depth, \( \tau \), from neutral hydrogen within (\( \tau_d \), dark) and outside (\( \tau_a \), light gray) the HII Region for the same LOS shown in the middle panel.

FIG. 2: Upper panel: Probability distribution function for \( R_d \) and \( R_f \) (physical units) using 1000 lines of sight (LOS) through the simulation box. The offset between the two distributions quantifies the apparent shrinking (see text). Central panel: Illustrative template (dashed line) and absorbed (solid dark) spectra, along with the \( n_{HI} \) density distribution (light gray) as a function of observed wavelength, for a representative LOS. Bottom panel: Contributions to the total GP optical depth, \( \tau \), from neutral hydrogen within (\( \tau_d \), dark) and outside (\( \tau_a \), light gray) the HII Region for the same LOS shown in the middle panel.
with physical distance from the quasar due to flux geometrical dilution and attenuation. Close to the edge we find $\tau_e \approx 400$, on average.

The apparent shrinking introduces a mean systematic underestimate of the physical HII region size, $R_d$, by $\Delta R = (R_d - R_f)/R_d = 0.32$ which translates into an overestimate of the $x_{HI}$ by a factor $\approx 3$.

### III. TRANSVERSE PROXIMITY EFFECT

In this section we show the details of the first-ever detection of transverse proximity effect in the HI Lyα forest. The presented study of the transverse proximity effect is based on the semi-analytical modeling by Gallerani et al. (2006).

Mahabal et al. (2005) have discovered a faint quasar (RD J1148+5253, hereafter QSO1) at $z = 5.65$ in the field of the highest redshift quasar currently known (SDSS J1148+5251, hereafter QSO2) at $z = 6.42$. We analyze the QSO2 transmitted flux, in order to study the proximity effect of QSO1 on the QSO2 spectrum. The two quasars have a projected separation of 109”, which corresponds to $R_L = 0.66$ Mpc. The line of sight to QSO2 intersects the bubble produced by QSO1 for a redshift path ($\Delta z_{prox}$) whose length depends on the radius of the HII region ($R_d$) itself. We find $R_d = 39$ Mpc, by plugging in Eq. 3 the following values: $t_Q = 1.34 \times 10^7 \text{yr}$, $x_{HI} = 8.4 \times 10^{-3}$, $N_L = 8.6 \times 10^{55} \text{sec}^{-1}$, where $x_{HI}$ is taken from the results by Gallerani et al. (2008), while $N_L$ is compatible with the luminosity of a quasar 3.5 magnitudes fainter than QSO2 (Mahabal et al. 2005). Given $R_d$, the region $\Delta z_{prox}$ extends from $z = 5.36$ up to $z = 5.97$. We re-compute $x_{HI}$ along the LOS to QSO2, adding to the general UVB photoionization rate $\Gamma_{HI}$ the photoionization rate $\Gamma_{HI}^{QSO1}$ provided by QSO1, given by:

$$\Gamma_{HI}^{QSO1} = \left(\frac{\alpha - 1}{\alpha + 2}\right) \frac{N_L \sigma_0}{4\pi R^2}, \quad (4)$$

where $\alpha = 1.5$ is the spectral index of the quasar continuum, $R$ is the distance from QSO1 to the LOS, $\sigma_0$ is the HI photoionization cross-section.

In Figure 3 we compare the observed transmitted flux in the spectrum of QSO2 with the simulated fluxes along 3 different LOS with (bottom row) or without (top) including the contribution from QSO1 to the total ionizing flux. For brevity, I refer to these case as “with bubble” or “without bubble”. Visual inspection of Figure 3 shows that the case “with bubble” is in better agreement with observations. Such statement can be made more quantitative by introducing a quantity denoted Peak Spectral Density (PSD), i.e. the number of transmissivity peaks per unit $\lambda_{RF}$ interval. For both the observed and simulated spectra, we compute the PSD inside and outside the bubble, finding the following results:

$$(PSD_{obs}^{OUT}, PSD_{obs}^{IN}) = (0.11, 0.40);$$

$$(PSD_{sim}^{OUT}, PSD_{sim}^{IN}) = (0.04^{+0.06}_{-0.04}, 0.24^{+0.35}_{-0.24}).$$

Observationally, the PSD is found to be $\approx 4$ times larger inside that bubble than outside it. This boost is quite well reproduced by the simulated PSD, although their absolute values are somewhat lower than the observed...
FIG. 4: Evolution of the optical depth $\tau$ as a function of the distance $R$ from QSO1. Filled circles denote the observed mean value for $\tau$, while error bars represent the maximum and the minimum observed $\tau$ at a given distance from the foreground quasar. Solid (dotted) magenta lines are the mean (maximum/minimum) values from 500 simulated LOS, computed adopting the case “with bubble”. Yellow (dashed) and black (dashed-dotted) lines represent the maximum and the minimum observed $\tau$ for the LOS located outside the quasar HII bubble. Filled black points at 1-$\sigma$ confidence level for 86% of the fitted 500 mock spectra through the simulated quasar environment we found that the HII region size deduced from quasar spectra, $R_f$, typically underestimates the physical one by 30 per cent, effect to which we refer to as apparent shrinking. This means that measurements of $x_H$ through the analysis of the proximity effect along the line of sight overestimate the actual neutral hydrogen fraction if the apparent shrinking effect is not taken into account (but see also Maselli et al. 2009).

As a final test for the presented model, we computed the observed evolution of the optical depth as a function of the distance $R$ from QSO1 and compare it with the predictions of model “with bubble”; the result is shown in Figure 4. The agreement between observations and simulations is at 1-$\sigma$ confidence level for 86% of the plotted points. For $R \lesssim 2$ Mpc, the mean optical depth $1.5 \lesssim \bar{\tau} \lesssim 3.5$ is lower than the mean value expected at $z = 5.65$ ($\bar{\tau}_z \approx 4$); it approaches $\bar{\tau}_{5.65}$ at distances larger than $R_e \approx 2$ Mpc. By taking the difference between $R_e$ and $R_\perp$, this study allows to set a lower limit on the foreground quasar lifetime $t_Q > \frac{R_e-R_\perp}{c} + (t_\tau - t_{QSO1}) \approx 11$ Myr, where $t_\tau$ and $t_{QSO1}$ represent the cosmic times corresponding to the redshifts $z_\tau = 5.68$ and $z_{em}^QSO1 = 5.65$, respectively.

IV. CONCLUSIONS

The proximity effect has been appreciated as a tool to investigate on the ionization level of the Universe at redshifts approaching the reionization epoch, and to study the environment and properties of quasars.

Radiative transfer calculations, combined with multiphase SPH simulations, have been used to investigate the possibility of constraining the ionization state of the IGM at $z \approx 6$ by measuring the size of the HII regions in high-$z$ quasars spectra. By deriving and analyzing mock spectra through the simulated quasar environment we found that the HII region size deduced from quasar spectra, $R_f$, typically underestimates the physical one by 30 per cent, effect to which we refer to as apparent shrinking. This means that measurements of $x_H$ through the analysis of the proximity effect along the line of sight overestimate the actual neutral hydrogen fraction if the apparent shrinking effect is not taken into account (but see also Maselli et al. 2009).

Moreover, we studied the case of an intervening HII region produced by the faint quasar RD J1148+5253 (QSO1) at $z = 5.65$ along the LOS toward the highest redshift quasar currently known (SDSS J1148+5251, QSO2) at $z = 6.42$. We analyzed the proximity effect of QSO1 on the QSO2 spectrum, by building up a simple model to estimate the location/extension of the proximity zone. Within the proximity region of QSO1 we found an increased number of peaks per unit frequency with respect to segments of the LOS located outside the quasar HII bubble. Moreover, we computed the observed evolution of the optical depth as a function of the distance $R$ from QSO1 and compared it with the predictions of the theoretical model. The agreement between observations and simulations is at 1-$\sigma$ confidence level for 86% of the plotted points. For $R \lesssim 2$ Mpc, the mean optical depth $1.5 \lesssim \bar{\tau} \lesssim 3.5$ is lower than the mean value expected at $z = 5.65$ ($\bar{\tau}_z \approx 4$); it approaches $\bar{\tau}_{5.65}$ at distances larger than $R_e \approx 2$ Mpc. By taking the difference between $R_e$ and $R_\perp$, this study allows to set a lower limit on the foreground quasar lifetime $t_Q > \frac{R_e-R_\perp}{c} + (t_\tau - t_{QSO1}) \approx 11$ Myr, where $t_\tau$ and $t_{QSO1}$ represent the cosmic times corresponding to the redshifts $z_\tau = 5.68$ and $z_{em}^QSO1 = 5.65$, respectively.
pected at $\bar{z} = 5.65$ ($\tau_{5.65} \approx 4$); it approaches $\tau_{5.65}$ at distances larger than $R_\tau \approx 2$ Mpc, thus providing a strong lower limit on QSO1 lifetime of $t_Q > 11$ Myr. The above results support the idea that the LOS to QSO2 is indeed sampling the proximity region of QSO1.

It is worth noting that searches for the transverse proximity effect in the HI Ly$\alpha$ forest at $z \approx 3$ (e.g. Schirber et al. 2004) have been so far unsuccessful. Such effect has been identified only by HeII absorption studies (Worseck & Wisotzki 2006; Worseck et al. 2007). Thus, the results shown represent the first-ever detection of the transverse proximity effect in the HI Ly$\alpha$ forest.

Acknowledgments

SG is grateful to A. Maselli, A. Ferrara, X. Fan, T. Roy Choudhury, collaborators of the work presented in this proceeding.

Published under licence in Journal of Physics: Conference Series by IOP Publishing Ltd.

[1] G. Becker et al., 2006, ApJ, 662, 72
[2] J. S. Bolton & M. G. Haehnelt, 2007, MNRAS, 374, 493
[3] X. Fan et al., 2002, AJ, 123, 1247
[4] X. Fan et al., 2006, ApJ, 132, 117
[5] S. Gallerani et al., 2006, MNRAS, 370, 1401
[6] S. Gallerani et al., 2008, MNRAS, 386, 359
[7] A. Mahabal et al., 2005, ApJ, 634, L9
[8] A. Maselli et al., 2005, MNRAS, 345, 379
[9] A. Maselli et al., 2007, MNRAS, 376, 34
[10] A. Maselli et al., 2009, MNRAS, 395, 1925
[11] A. Mesinger & Z. Haiman, 2004, ApJ, 611, L69
[12] M. Schirber et al., 2004, ApJ, 610, 105
[13] V. Springel & L. Hernquist, 2003, MNRAS, 339, 312
[14] R. Teller et al., 2002, ApJ, 565, 773
[15] G. Worseck & L. Wisotzki, 2006, A & A, 450, 495
[16] G. Worseck et al., 2007
[17] J. S. B. Wyithe et al., 2005, ApJ, 628, 575
[18] J. S. B. Wyithe & A. Loeb, 2006, ApJ, 646, 696
[19] Q. Yu & Y. Lu, 2005, ApJ, 620, 31