What can we learn from quasar absorption spectra?

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We analyze optical-near infrared spectra of a large sample of quasars at high redshift with the aim of investigating both the cosmic reionization history at \( z \approx 6 \) and the properties of dust extinction at \( z > 4 \). In order to constrain cosmic reionization, we study the transmitted flux in the region blueward the Ly\( \alpha \) emission line in a sample of 17 quasars spectra at \( 5.7 \leq z_{\text{em}} \leq 6.4 \). By comparing the properties of the observed spectra with the results of a semi-analytical model of the Ly\( \alpha \) forest we find that actual data favor a model in which the Universe is highly ionized at \( z \approx 6 \), thus being consistent with an epoch of reionization at higher redshifts. For what concerns the study of the high-z dust, we focus our attention on the region redward the Ly\( \alpha \) emission line of 33 quasars at \( 4 \leq z_{\text{em}} \leq 6.4 \). We compute simulated dust-absorbed quasar spectra by taking into account a large grid of extinction curves. We find that the SMC extinction curve, which has been shown to reproduce the dust reddening of most quasars at \( z < 4 \), is not a good prescription for describing dust extinction also at higher redshifts.

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I. INTRODUCTION

Quasar absorption spectra retain a huge amount of information on the ionization level of the intergalactic medium (IGM), therefore being exquisite tools for studying the cosmic reionization process.

Moreover, the dust present in the host galaxy of a quasar affects its spectrum, preferentially absorbing the blue part of the rest frame ultraviolet quasar continuum, effect generally called “reddening”.

In what follows we discuss the interpretation of a sample of almost 50 quasars observed at \( z > 4 \) in terms of the neutral hydrogen and dust content in the early Universe.

II. COSMIC REIONIZATION

After the recombination epoch at \( z \approx 1100 \), the Universe remained almost neutral until the first generation of luminous sources (stars, accreting black holes, etc...) were formed. The photons from these sources ionized the surrounding neutral medium and once these individual ionized regions started overlapping, the global ionization and thermal state of the intergalactic gas changed drastically. This is known as the reionization of the Universe, which has been an important subject of research over the last few years, especially because of its strong impact on the formation and evolution of the first cosmic structures (for a comprehensive review on the subject of reionization and first cosmic structures, see Ciardi and Ferrara [3].

Although observations of cosmic epochs closer to the present have indisputably shown that the IGM is in an ionized state, it is yet unclear when the phase transition from the neutral state to the ionized one started. Thus, the redshift of reionization, \( z_{\text{rei}} \), is still very uncertain.

In the last few years a possible tension has been identified between WMAP5 data [4] and SDSS observations of quasar absorption spectra [1], the former being consistent with an epoch of reionization \( z_{\text{rei}} \approx 11 \), the latter suggesting \( z_{\text{rei}} \approx 6 \). Long Gamma Ray Bursts may constitute a complementary way to study the reionization process, possibly probing \( z > 6 \) (e.g. Salvaterra et al. [5]). Moreover, an increasing number of Lyman Alpha Emitters are routinely found at \( z > 6 \) (e.g. Stark et al. [6]).

In this work, we analyze statistically the transmitted flux of 17 quasar absorption spectra observed at \( 5.7 \leq z_{\text{em}} \leq 6.4 \) in order to understand whether current data of quasars absorption spectra strongly require a sudden change in the global properties (temperature, ionization level, etc...) of the Universe at \( z \approx 6 \), or they are still compatible with a highly ionized IGM at these redshifts.

A. The Ly\( \alpha \) forest

The radiation emitted by quasars could be absorbed through Ly\( \alpha \) transition by the neutral...
FIG. 1: Left panel: Evolution of the volume filling factor of ionized regions for the early (red solid lines) and late (blue dotted lines) reionization models. Middle panel: Evolution of the neutral hydrogen fraction. Thick lines represent average results over 100 lines of sight (LOS), while the thin lines denote the upper and lower neutral hydrogen fraction extremes in each redshift interval. Solid circles represent neutral hydrogen fraction estimates by Fan et al. [1]; empty squares denote the results obtained in this work. Right panel: Evolution of the Gunn-Peterson optical depth for early (ERM, solid red line) and late (LRM, blue dotted). Thick lines represent average results on 100 LOS for each emission redshift, while the thin lines denote the upper and lower transmission extremes in each redshift bin, weighted on 100 LOS. Filled and empty circles are observational data from Songaila [2] and Fan et al. [1], respectively.

FIG. 2: Largest Gap Width distribution for the LR and the HR cases (left and right, respectively). Filled circles represent the result of the analysis of the 17 quasars observed spectra. Solid red (dotted blue) lines show the results obtained by the semi-analytical modeling implemented for the ERM (LRM). Vertical error bars measure poissonian noise, horizontal errors define the bin for the gap widths.

hydrogen intersecting the line of sight, the so-called Gunn-Peterson (GP) effect [3]. The Lyα forest arises from absorption by low amplitude-fluctuations in the underlying baryonic density field. To simulate the GP optical depth ($\tau_{GP}$) distribution we use the method described by Gallerani et al. [8], whose main features are recalled in the following. The spatial distribution of the baryonic density field and its correlation with the peculiar velocity field are taken into account adopting the formalism introduced by Bi & Davidsen (1997). To enter the mildly non-linear regime which characterizes the Lyα forest absorbers we use a Log-Normal model, firstly introduced by Coles and Jones [9].
B. Reionization models

For a given IGM temperature, the neutral hydrogen fraction, $x_{\text{HI}}$, can be computed from the photoionization equilibrium as a function of the baryonic density field and photoionization rate due to the ultraviolet background radiation field. For all these quantities we follow the approach introduced by Choudhury and Ferrara [14], hereafter CF06. By assuming as ionizing sources quasars, PopII and PopIII stars, their model provides excellent fits to a large number of observational data, namely the recombination evolution of Lyman-limit systems, Lyα and Lyβ optical depths, electron scattering optical depth, cosmic star formation history, and the number counts of high redshift sources. In the CF06 model, a reionization scenario is defined by the product of two free parameters: (i) the star-formation efficiency $f_s$, and (ii) the escape fraction $f_{\text{esc}}$ of ionizing photons of PopII and PopIII stars. We select two sets of free parameters values yielding two different reionization histories: (i) an Early Reionization Model (ERM), for $f_{s,\text{PopII}} = 0.1$; $f_{\text{esc,PopII}} = 0.07$, and (ii) a Late Reionization Model (LRM), for $f_{s,\text{PopII}} = 0.08$; $f_{\text{esc,PopII}} = 0.04$. The properties of the two models considered are shown in Figure 1. The left panel shows the evolution of the volume filling factor of ionized regions, from which it results that in the LRM (blue dotted line) the epoch of reionization is $z_{\text{rei}} \sim 6$, while in the ERM (red solid line) $z_{\text{rei}} \sim 7$, meaning that in this case the Universe is highly ionized at $z \sim 6$. In the middle panel the volume averaged neutral hydrogen fraction $x_{\text{HI}}$ is plotted for the two models, and in the right panel the corresponding optical depth evolution is shown.

C. Observational constraints on cosmic reionization

Since at $z \approx 6$ regions with high transmission in the Lyα forest become rare, an appropriate method to analyze the statistical properties of the transmitted flux is the distribution of gaps. A gap is defined as a contiguous region of the spectrum characterized by a transmission above a given flux threshold ($F_{\text{th}} = 0.08$ in this work). In particular Gallerani et al. [8] suggested that the Largest Gap Width statistics are suitable tools to study the ionization state of the IGM at high redshift. The LGW distribution quantifies the fraction of lines of sight (LOS) which are characterized by the largest gap of a given width. We apply the LGW statistics both to simulated and observed spectra with the aim of measuring the evolution of $x_{\text{HI}}$ with redshift.

We use observational data including 17 quasars obtained by Fan et al. [1]. We divide the observed spectra into two redshift-selected sub-samples: the “Low-Redshift” (LR) sample (8 emission redshifts $5.7 < z_{\text{em}} < 6$), and the “High-Redshift” (HR) one (9 emission redshifts $6 < z_{\text{em}} < 6.4$). The comparison between the simulated and the observed results for the LGW statistics is shown in Figure 2. In the LR (HR) sample, the quasars emission redshifts used and the wavelength interval analyzed in the spectra are such that the mean redshift of the absorbers is $\langle z \rangle = 5.3$ ($\langle z \rangle = 5.6$). From the good agreement between the simulated and the observed LGW distribution it results that the $x_{\text{HI}}$ evolves smoothly from $10^{-4.4}$ at $z = 5.3$ to $10^{-4.2}$ at $z = 5.6$. However, it is also clear from the figure that the ERM is in better agreement with observations. We find that actual data favor a highly ionized Universe at $z \sim 6$, with a robust upper limit $x_{\text{HI}} < 0.36$ at $z = 6.3$ [11].

III. DUST AT HIGH REDSHIFT

Dust represents one of the key ingredients of the universe by playing a crucial role both in the formation and evolution of the stellar populations in galaxies as well as in their observability. The presence of dust is shown by several observational evidences covering a large redshift interval, ranging from our Galaxy to the frontiers of the observable Universe.

Richards et al. [12] and Hopkins et al. [13] have found that, at $z < 2$, reddened quasars (including Broad Absorption Line, BAL, quasars) are characterized by the extinction curve of the Small Magellanic Cloud (SMC).

This result is in disagreement with the analysis of the reddened quasar SDSSJ1048+46 at $z = 6.2$ [14] and of the spectral energy distribution of the Gamma Ray Burst GRB050904 afterglow at $z = 6.3$ [15]. These studies show that the inferred dust extinction curves are different with respect to those observed at low redshift, while being in very good agreement with the Tdini and Ferrara [16] predictions of dust formed in SNe ejecta.

Here, we apply a similar analysis to a sample of 33 observed quasars at $4 \leq z_{\text{em}} \leq 6.4$ to un-
understand whether the SMC extinction curve is a good prescription for describing dust extinction at these redshifts.

Observational data are from Juarez et al. 17, Jiang et al. 18, Willott et al. 19, Mortlock et al. 20.

A. Extinction curves

In order to investigate the evolution of the dust properties across cosmic times, we consider a grid of extinction curves to characterize the extinction produced by dust in the rest-frame wavelength range $0.1 \leq \lambda \leq 0.5 \mu m$. First, we consider the empirical curves which describe the dust extinction in the local Universe 21: the Milky Way (MW) extinction curve, characterized by a prominent bump at 2175 Å; the featureless Small Magellanic Cloud (SMC) extinction curve, which steeply rises with inverse wavelength from near infrared to far ultraviolet ($A_\lambda/A_{3000} \sim \lambda^{-1/2}$); the Large Magellanic Clouds (LMC) extinction curve, being intermediate between the MW and the SMC. We show the SMC, LMC and MW extinction curves in Figure 3, left panel (black solid, red dotted, green dashed lines, respectively).

We also use the extinction curves expected by Type II SNe dust models as predicted by Todini and Ferrara 22, Bianchi and Ferrara 16 depend on the metallicity of the SNe progenitors; the middle panel of Figure 3 shows the cases of $Z = 0$ (TF1, magenta solid line), $Z = Z_{\odot}$ (TF2, green dotted line), and $Z = 10^{-2}Z_{\odot}$ (TF3, red dotted-long-dashed line). For what concerns the models by Bianchi and Schneider 22, these authors take into account the possibility that the freshly formed dust in the SNE envelopes can be destroyed and/or reprocessed by the passage of the reverse shock.

The middle panel of Figure 3 shows the extinction curve predicted by the model before the passage of the reverse shock, assuming solar metallicity for the SNe progenitor.

In the right panel of Figure 3 we show the results of the models by Hirashita et al. 23 for dust produced by Pair Instability SNe (PISN) having progenitor mass of 170 $M_{\odot}$. Hirashita et al. 23 study two extreme cases for the mixing of the elements constituting the dust grains: the first one is the unmixed case, in which the original onion-like structure of elements is preserved in the helium core; the second one is the mixed case, characterized by a uniform mixing of the elements. In the bottom right panel of Figure 3 we show the results of their analysis in the mixed (PISN1, solid magenta line) and unmixed (PISN2, dotted green line) cases.

B. Observational constraint on the high-z dust

We fit the spectral region redward the Ly$\alpha$ emission line with the following equation:

$$F_{\lambda} = C \left( \frac{\lambda}{3000} \right)^{(1.62 - \alpha)} \left( 10^{-A_{3000} \frac{\lambda}{3000}} \right),$$

where $C$ is a normalization constant, $F_{\lambda}$ is a quasar template spectrum, $\alpha$ the slope of the unreddened spectrum, $A_{3000}$ the absolute extinction at 3000 Å, and $A_\lambda$ the extinction curve normalized at 3000 Å. In this study we adopt the template by Reichard et al. 24, obtained considering 892 quasars classified as non-BAL. The spectral index of the averaged non-BAL spectrum ($F_{\lambda} \propto \lambda^{-\alpha_t}$) is $\alpha_t = 1.62$. Therefore, the term $(\lambda/3000)^{(1.62 - \alpha)}$ allows us to force the slope of the template to the value $\alpha$. We let $\alpha$ to vary in the interval [0.2; 3.0], which is the range encompassed by more than 95% of the quasars. For each quasar spectra, in the fitting procedure, we avoid the emission features characterizing the following spectral regions in the rest frame of the source: Lyo+NV [1215.67; 1280] Å; OI+SiII [1292; 1320] Å; SiIV+OIV [1380; 1418] Å; CIV [1515; 1580] Å; AIII+CIII [1845; 1945] Å. We also exclude the region [2210; 3000] Å, characterized by a prominent FeII bump. After having selected the spectral regions to be included in the analysis, we rebin the observed spectra to a resolution $R \sim 50$, which is about the spectral resolution delivered by the Amici prism in the NICS-TNG observations.

The $\chi^2$ analysis reveals that 7 quasars require substantial ($A_{3000} \geq 0.8$) reddening and that these reddened spectra favor extinction curves which differ from the SMC. This study mostly aims at investigating whether the properties of the extinction curves at $z \gtrsim 4$ deviate or not from the SMC, which has been shown to reproduce the dust reddening of quasars at $z < 4$. Therefore, we compute the mean of the inferred...
FIG. 3: **Left panel:** Empirical curves for dust extinction in the local Universe [21]. **Middle panel:** Theoretical extinction curves predicted by Type II SNe dust models proposed by CitetTodiniFerrara2001 and Bianchi and Schneider [22]. **Right panel:** Predictions for extinction curves produced by PISNe dust [23].

FIG. 4: The mean extinction curve (MEC) computed by combining the results obtained for individual quasars is shown through black filled squares, along with the 1σ dispersion denoted by the error bars.

extinction curves to provide an empirical, average extinction law at \( z \gtrsim 4 \), called MEC, and shown in Fig. 4. We find that the MEC deviates from the SMC extinction curve at a confidence level \( \gtrsim 90\% \) for \( \lambda < 2000 \) Å in the rest frame of the source [23].

IV. CONCLUSIONS

We analyze optical-near infrared spectra of a large sample of quasars at high redshift with the aim of investigating both the cosmic reionization history at \( z \sim 6 \) and the properties of dust extinction at \( z > 4 \).

In order to investigate cosmic reionization, we study the transmitted flux in the region bluerward the Lyα emission line in a sample of 17 quasars spectra at \( 5.7 \leq z_{em} \leq 6.4 \). We analyze the wide dark portions (gaps) in the observed absorption spectra and we compare the statistics of these spectral features with a semi-analytical model of the Lyα forest. We consider two physically motivated reionization models: (ii) a Late Reionization Model LRM in which the epoch of reionization is \( z_{rei} \sim 6 \); (ii) an Early Reionization Model in which \( z_{rei} \sim 7 \), meaning that in this case the Universe is highly ionized at \( z \sim 6 \). We find that the volume-averaged neutral hydrogen fraction \( x_{HI} \) evolves smoothly from \( 10^{-4.4} \) at \( z = 5.3 \) to \( 10^{-4.2} \) at \( z = 5.6 \), with a robust upper limit \( x_{HI} < 0.36 \) at \( z = 6.3 \). The frequency and physical sizes of the gaps favor the ERM, thus being consistent with an highly ionized IGM at \( z \sim 6 \). This result is also confirmed by the analysis of the optical afterglow.
spectrum of the Gamma Ray Burst GRB050904 at $z = 6.3$ \cite{26} and by the evolution of the luminosity function of Ly$\alpha$ emitters between $z = 5.7$ and $z = 6.6$ \cite{27}.

For what concerns the study of the high-$z$ dust, we focus our attention on the region redward the Ly$\alpha$ emission line of 33 quasars observed at $4 \leq z_{em} \leq 6.4$. We compute simulated absorbed quasar spectra by taking into account a large grid of extinction curves which includes well-known empirical laws describing the dust extinction of the local Universe, namely the SMC, the LMC, and the MW extinction curves, as well as several theoretical extinction curves predicted by supernova dust models. We apply a $\chi^2$ analysis to the observed spectra, by comparing them with the synthetic absorbed ones. We find that 7 quasars in our sample require substantial ($A_{3000} \geq 0.8$) reddening. Since the SMC extinction curve has been shown to reproduce the dust reddening of most quasars at $z < 4$, the main goal of this work is to investigate whether this curve provides a good prescription for describing dust extinction also at higher redshifts. Starting from the results obtained for individual quasars, we compute an empirical mean extinction curve (MEC) with the corresponding standard deviation. We find that the MEC deviates from the SMC extinction curve at a confidence level $\gtrsim 68\%$ for $\lambda < 2000$ $\AA$ in the rest frame of the source. This result suggests that the properties of dust (chemical composition and/or grain size distribution) may differ at $z > 4$ with respect to the local Universe \cite{25}.

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