Thermal state of the intergalactic medium near to the optical limit for the Ly-α forest

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Abstract
In this article, the temperature-density relation of the intergalactic medium was studied in the region 1.6 ≤ z < 2.0 divided into two bins. For this purpose, the Ly-α forest decomposition into individual absorption profiles was used for the study of 35 publicly available quasar spectra obtained by the Ultraviolet and Visual Echelle Spectrograph (UVES) on the Very Large Telescope (ESO) and by the High Resolution Echelle Spectrometer (HIRES) on the Keck Telescope. For the determination of the thermal state sensitive cut-off position in the $b - N_{\text{HI}}$ distribution, the iterative fitting procedure was adopted. The measurements were calibrated using mock Ly-α forest data generated by 23 hydrodynamical simulations with different thermal histories. The value of the temperature at mean density corresponds to the decreasing trend predicted by various models at the lower redshifts. In the case of power law index, determined values are close to 1.6, which is expected after all reionization events in various models assuming the balance of photoheating with adiabatic cooling.

Key words: cosmology: early Universe – quasars: absorption lines – intergalactic medium

1 INTRODUCTION
The physical conditions of the intergalactic medium (IGM) could be studied by analysis of the so-called Ly-α forest in quasar (QSO) spectra. Hui & Gnedin (1997) showed that for gas overdensities $δ ≤ 10$, the temperature is related to the density throughout a power-law in the form

$$T = T_0(1 + δ)^{γ−1}, \quad (1)$$

where $T_0$ is the temperature of the IGM at the mean density and $γ$ is the power-law index. If we determine the parameters $T_0$ and $γ$ as a function of redshift, we can describe the thermal history of the IGM.

Various approaches were used for the characterization of the $T – ρ$ relation of the IGM from Lyman-α absorption forest. As an example, the approach that treats the Ly-α forest as a superposition of discrete absorption profiles (Schaye et al. 1999; Ricotti et al. 2000; Torrela et al. 2018; Hiss et al. 2018), analysis of the flux probability distribution function by Bolton et al. (2008) and Viel et al. (2009), the power spectrum of the transmitted flux (Zaldarriaga et al. 2001; Theuns et al. 2002; Walther et al. 2019), the average local curvature (Becker et al. 2011) and Boera et al. (2014) and wavelet decomposition (Lidz et al. 2010).

Most studies deal with the characterization of the $T – ρ$ relation of the IGM around $z ≲ 3$, which is interesting due to the HeII reionization. Unlike of this redshift, for which is possible to find $≤ 300$ Ly-α absorption lines in QSO spectra, for $z ≈ 2$, there are typically less than 100 absorption lines with $log N_{\text{HI}} ∈ (12.5 – 14.5)$ between the Ly-α and Ly-β emission lines (Schaye et al. 1999). Generally, the number density of the Ly-α forest decreases with the decreasing redshift, and $z ≈ 1.5$ is considered as the optical limit for the Ly-α forest (Boera et al. 2014).

The temperature in this lower redshift region was firstly studied by Boera et al. (2014) using the curvature measurement. For the mean redshift $z = 1.63$, the authors determined the temperature $(20.66 ± 2.03) × 10^3$ K and $(13.00 ± 1.27) × 10^3$ K at the mean density assuming the values of $γ = 1.3$ and $1.5$, respectively. For the higher value of mean redshift $(z = 1.82)$, the authors determined the values of temperature $T_0(γ ≈ 1.3) = (17.61 ± 0.76) × 10^3$ K and $T_0(γ ≈ 1.5) = (11.79 ± 0.51) × 10^3$ K. Based on the results from the redshift range $1.5 ≤ z ≤ 2.8$, the authors of this study found a decrease in temperature with decreasing redshift, which could be interpreted as a trace of completion of the reheating process related to the HeII reionization.

Walther et al. (2019) presented the fiducial evolution of thermal parameters in the region $1.8 < z < 5.4$ using the Ly-α flux power spectrum. Assuming the strong prior on mean transmitted flux $F$, the corresponding values of the temperature $T_0$ and power-law index $γ$ are $(7.68^{+3.69}_{−2.18} × 10^3$ K and $1.63^{+0.16}_{−0.25}$ at the redshift $z = 1.8$, respectively.

It is worth noting that Schaye et al. (2000) also studied the region $1.85 ≤ z ≤ 2.09$ using the spectrum of only one quasar (Q1100-264). For the median value of the redshift $z = 1.96$, the authors determined value of $T_0(11 000$ K and $γ = 1.4$. In this case, the analysis of IGM was based on the Voigt profile decomposition of the Ly-α forest into the set of individual absorption lines.

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2. DATA AND ANALYSIS

In this study, the sample of 35 publicly available quasar spectra were used for analysis. The first part of the sample consists of 13 QSO spectra from KODIAQ (Keck Observatory Database of Ionized Absorption toward Quasars) survey (Lehner et al. 2014; O’Meara et al. 2015, 2017), which is a repository of reduced, continuum normalized spectra obtained by the High-Resolution Echelle Spectrometer (HIRES) on the Keck Telescope. These spectra were observed between years 1995–2012 and subsequently uniformly reduced and continuum fitted by eye by KODIAQ team (O’Meara et al. 2015). The second part of the sample contains of 22 QSO spectra obtained by the Ultraviolet and Visual Echelle Spectrograph (UVES) on the VLT/ESO (Murphy et al. 2019). The UVES Spectral Quasar Absorption Database comprises fully reduced, continuum-fitted high-resolution spectra of quasars in the redshift range 0 < z < 5. From the whole dataset we selected only spectra that meet the following criteria:

(i) the QSO spectrum covers at least Δz = 0.1 of at least one considered redshift bin,
(ii) the spectrum does not contain large gaps that would not allow the correct identification of metal lines,
(iii) the signal-to-noise (S/N) ratio of the spectrum is higher than 10 in the studied spectral region.

The list of 35 QSOs whose spectra were used in this study with their basic characteristics is presented in Table 1. The redshift coverage of the analysed QSO spectra is shown in Fig. 1. We studied the effects of continuum misplacement on the achieved results and showed its effect is negligible in the case of our data. A detailed description of the analysis can be found in Appendix A.

2.1 Voigt profile fitting

In this study, the VPFIT code written by R. F. Carswell and J. K. Webb (Carswell & Webb 2014) was used. The QSO spectra were analyzed within the following parameter space: b = 1 – 300 km s⁻¹ and logN_HI = 11.5 – 16.0. The rest-frame wavelengths 1050 – 1180 Å inside the Ly-α forest were chosen for the Voigt profile fitting to avoid proximity effects, i.e. a region affected by the local QSO radiation (exclude the Ly-β and O VI 1035 emission lines) rather than the metagalactic ultraviolet background (UVB; Palanque-Delabrouille et al. 2013; Walther et al. 2018; Hiss et al. 2018).

The Ly-α absorbers corresponding to the damped Ly-α (DLA) systems with logN_HI ≥ 20 and also sub-damped Ly-α (sub-DLA) systems were identified by eye and excluded from the analysis. Each spectrum was also visually observed for bad points and gaps, which were subsequently masked and cubically interpolated. Relative errors
of 1% were given to such spectral regions, so the Voigt profile fitting procedure was not influenced (Hiss et al. 2018). An example of the decomposition of the Ly-\(\alpha\) forest into individual absorption lines in the spectrum of QSO J122824+312837 is shown in Fig. 2.

2.2 Metal lines rejection

Quasar spectra also contain various metal absorption lines, which can affect the obtained results. They are usually related to the high H1 absorption, and can be identified via associations with other ionic metal lines. From this reason, we used DLA and sub-DLA systems and determined their redshifts with help of the associated C\(\text{v}\), Si\(\text{iv}\), Mg\(\text{ii}\) metal lines redward of the Ly-\(\alpha\) emission peak. It is worth noting that in the case of metal absorption lines not related with DLA systems (mostly within the data coverage), we used the doublets of Si\(\text{iv}\), C\(\text{v}\) and Mg\(\text{ii}\) to determine the redshift of metal absorption systems. If the redshifts were known, the other metal lines (see Tab. 2) were determined based on their characteristic \(\Delta\lambda\).

After the identification, the procedure for the metal line rejection in both cases can be, in general, described as follows: firstly, we fitted the studied intervals unmasked of identified lines to minimise the impact of possible adverse effects of masking on the Voigt profile fitting. After this step, we excluded the previously identified metal lines from the VPFIT output so that they do not affect the results of our analysis. Example of the metal lines rejection procedure based on the sub-DLA system at \(z \approx 1.839\) in the spectrum of QSO J110325–264515 is shown in Fig. 3.

As was described by Hiss et al. (2018), we also tested if the remaining absorbers below the lower envelope of the \(b–N_{\text{H1}}\) distribution belong to the metal lines listed in Tab. 2. We would like to note that if the absorber candidate was identified only as a single or doubtful doublet feature, we did not consider it as a metal line.

2.3 The \(b–N_{\text{H1}}\) distributions

The VPFIT outputs were used to generate the \(b–N_{\text{H1}}\) distributions, from which parameters in the \(T–\rho\) relation could be determined. The \(b–N_{\text{H1}}\) distribution of the parameterized absorbers in the redshift range of \(1.6 < z < 2.0\) is plotted in Fig. 4. Firstly, we divided the results into two bins with the redshift range of \((1.6 – 1.8)\), and \((1.8 – 2.0)\). Then, the lower limit of \(b\) was chosen to \(10\text{ km s}^{-1}\) mainly due to the lines with lower values could be attributed to the ionic metal-line transitions (Hiss et al. 2018; Rauch et al. 1997). The lines with \(b > 100\ \text{km s}^{-1}\) were also excluded, which is a convention used for example by Rudie et al. (2012) and Hiss et al. (2018). The reason for such a choice is that the turbulent broadening dominates over the thermal one in these lines. In the case of the column density, the chosen range of \(12.5 \leq N_{\text{H1}} \leq 14.5\) corresponds to the gas density range for which the equation of state is well fitted by a power law (Schaye et al. 1999).

2.4 Narrow lines rejection

Although the aforementioned rejection procedure was applied, many narrow absorption lines in blends and unidentified metal lines with \(b \geq 10\text{ km s}^{-1}\) still remain in the results. Due to this fact, we used the similar iterative rejection algorithm as proposed by Hiss et al. (2018), which can be described as follows: firstly, we divided the absorbers with \(b < 40\text{ km s}^{-1}\) into eight \(\log N_{\text{H1}}\) bins of the same size. Then, the mean and standard deviation of the absorbers in every bin were calculated. After this step, we excluded all points below \(2\sigma\) of the mean. This procedure is iterated until no points are excluded. After the last iteration, we fitted the line to the \(\log b_{2\sigma}\) values of each \(\log N_{\text{H1}}\) bin. Finally, if the position of this line is determined, all absorbers below it are excluded.

2.5 Fitting the cut-off in the \(b–N_{\text{H1}}\) distribution

In this study, the iterative fitting procedure proposed by Schaye et al. (1999) was used to determine the position of the thermal state sensitive cut-off. It is based on the following equation

\[
\log b_{\text{th}} = \log b_0 + (\Gamma - 1) \log N_{\text{H1}}/N_{\text{H1,0}}.
\]

(2)

where \(b_{\text{th}}\) corresponds to the thermal Doppler broadening, \(b_0\) is the minimal broadening value at column density \(N_{\text{H1,0}}\) and \(\Gamma\) is the index of this power-law relation. Firstly, we fit the Eq. (2) to the points in the \(b–N_{\text{H1}}\) distribution using the least absolute deviations method. After this step, the mean absolute deviation is calculated as

\[
|\delta \log b| = \frac{1}{n} \sum_{i=1}^{n} |\log b_i - \log b_{\text{th}}(N_{\text{H1},i})|
\]

(3)

where \(n\) is the sample size. Subsequently, all points for which the value of the Doppler parameter \(b\) fulfills the condition

\[
\log b > \log b_{\text{th}} + |\delta \log b|
\]

(4)

are excluded in the next iteration. All these steps are repeated until no points are more than one absolute mean deviation above the fit. The last step is the exclusion of the points that are below the one absolute mean deviation of the last fit. The remaining points are then used for the final fit, from which \(b_0\) and \(\Gamma - 1\) are determined.

Table 2. List of identified metal lines with their oscillator strength \(f\).

| Absorber | \(\lambda_{\text{rest}}\) [Å] | \(f\) | Reference |
|----------|-----------------|---|----------|
| O\(\text{vi}\) | 1031.9261 | 0.13290 | 1 |
| C\(\text{ii}\) | 1036.3367 | 0.12310 | 1 |
| O\(\text{vi}\) | 1037.6167 | 0.06609 | 1 |
| N\(\text{ii}\) | 1083.9900 | 0.10310 | 1 |
| Fe\(\text{iii}\) | 1122.5260 | 0.16200 | 2 |
| Fe\(\text{ii}\) | 1144.9379 | 0.10600 | 3 |
| Si\(\text{ii}\) | 1190.4158 | 0.25020 | 1 |
| Si\(\text{ii}\) | 1193.2897 | 0.49910 | 1 |
| N\(\text{i}\) | 1200.2233 | 0.08849 | 1 |
| Si\(\text{iii}\) | 1206.5000 | 1.66000 | 1 |
| N\(\text{v}\) | 1238.8210 | 0.15700 | 1 |
| Si\(\text{v}\) | 1242.8040 | 0.07823 | 1 |
| Si\(\text{ii}\) | 1260.4221 | 1.00700 | 1 |
| O\(\text{i}\) | 1302.1685 | 0.04887 | 1 |
| Si\(\text{ii}\) | 1304.3702 | 0.09400 | 1 |
| C\(\text{ii}\) | 1334.5323 | 0.12780 | 1 |
| C\(\text{ii}\) | 1335.7077 | 0.11490 | 1 |
| Si\(\text{iv}\) | 1393.7550 | 0.52800 | 1 |
| Si\(\text{iv}\) | 1402.7700 | 0.26200 | 1 |
| Si\(\text{ii}\) | 1526.7066 | 0.12700 | 1 |
| C\(\text{iv}\) | 1548.1950 | 0.19080 | 1 |
| C\(\text{iv}\) | 1550.7700 | 0.09522 | 1 |
| Al\(\text{ii}\) | 1670.7874 | 1.88000 | 1 |
| Al\(\text{iii}\) | 1854.7164 | 0.53900 | 1 |
| Al\(\text{iii}\) | 1862.7895 | 0.26800 | 1 |
| Mg\(\text{ii}\) | 2796.3520 | 0.61230 | 6 |
| Mg\(\text{ii}\) | 2803.5310 | 0.30540 | 6 |

References: (1) Morton (1991), (2) Prochaska et al. (2001), (3) Howk et al. (2000), (4) Tripp et al. (1996), (5) Schectman et al. (1998), (6) Verner et al. (1996).
Figure 2. Resulting fit of the Ly-α forest in the spectrum of QSO J122824+312837. The original spectrum (grey line) is well described by the superposition of Voigt profiles fitted using the VPFIT code (red line).

Figure 3. Example of the metal lines rejection procedure based on the sub-DLA system at $z \approx 1.839$ in the spectrum of QSO J110325-264515 (upper panel). The associated C iv 1548, 1550 Å spectral lines redward of the Ly-α emission peak (bottom left panel) were used for more precise determination of the sub-DLA redshift. The Si ii 1190, 1193 Å spectral lines (bottom right panel) are related to the strong H i absorption depicted in upper panel. The red dashed lines represent the continuum level.

2.6 Estimation of the $N_{H_1,0}$

As we mentioned before, the value of $N_{H_1,0}$ is just a normalization. However, it is useful to choose its value that corresponds to the column density of a typical absorber at the mean density of the IGM (Hiss et al. 2018). Under the assumption of the local hydrostatic equilibrium in the low-density cloud, the relationship between $N_{H_1}$ and local overdensity $\Delta = \rho/\rho_0$ can be written as (Schaye 2001; Rudie et al. 2012)

$$N_{H_1,0} \approx 10^{13.23} \Delta^{3/2} \frac{T_4^{0.22}}{\Gamma_{ion,H_1}} \left(\frac{1+z}{3.4}\right)^{9/2} \text{cm}^{-2}. \quad (5)$$

where $\Gamma_{ion,H_1}$ is the photoionization rate of H i in units of $10^{-12}$ s$^{-1}$ and $T_4$ is the temperature of the absorbing gas in units of $10^4$ K.

In the case of simulations, the normalization factor $N_{H_1,0} = N_{H_1}(\Delta = 1)$ was calculated using the Eq. (5) for every single thermal model, which was used for calibration (see below). We would like to note that we used the effective UVB $\Gamma_{ion,H_1} = \Gamma_{ion,H_1,sim}/A_T$ as the used simulations were rescaled using the scaling factor $A_T$ (see Section 3.1). By including this step, we reduced the variation of $N_{H_1,0}$ with thermal parameters. In the case of simulation, the average value of $\log N_{H_1,0} = (12.8247 \pm 0.0872)$ cm$^{-2}$ over all of the thermal models was used for the cut-off fitting procedure.

In the case of analysed redshift bins, we calculate the normalization factor according to the equation (Hiss et al. 2018)

$$\log N_{H_1,0}(z) = 0.6225(1+z) + 11.1068. \quad (6)$$
Figure 5. $b - N_{\text{HI}}$ distributions are shown in left panels, where the red solid and blue dashed lines correspond to the best cut-off fits and the results of narrow-line rejection procedure, respectively. The overplotted red circles correspond to the log $N_{\text{HI},0}$. The right panels show the corresponding PDFs $p(b_0, \Gamma)$, where the 68% and 95% confidence levels are plotted by dark and light blue colors, respectively. The black points correspond to the medians of the marginal distributions of $b_0$ and $\Gamma$.

The reason for this choice is that we used the THERMAL suite (see below), which was also used in the aforementioned study to obtain the calibration between $b_0 - T_0$ and $\Gamma - \gamma$.

2.7 Cut-off fitting results

For the determination of the final cut-off parameters, we used the bootstrap resampling method with replacement. We generate 2000 datasets by bootstrapping of the cut-off fitting procedure, from which the probability distribution functions (PDFs) $p(b_0, \Gamma)$ were obtained. The medians of these distributions was used as the best estimates of the $b_0$ and ($\Gamma - 1$) parameters. We would like to note that the uncertainties correspond to the 16th and 84th percentiles of the probability distribution functions. The resulting $b - N_{\text{HI}}$ distributions together with the kernel density estimation of $p(b_0, \Gamma)$ for both studied redshift bins ($1.6 \leq z < 1.8$ and $1.8 \leq z < 2.0$) are plotted in Fig. 5.

3 SIMULATIONS

To obtain more accurate values of the temperature $T_0$ and power-law index $\gamma$, Bolton et al. (2014) suggested that calibration of the cut-off fitting measurements based on the simulations is needed. To reach this goal, we used the set of simulated skewers at redshift $z = 1.8$ from the THERMAL (Thermal History and Evolution in Reionization Models of Absorption Lines) $^1$ suite (for more details see Oñorbe et al. 2017). This dataset includes skewers from 88 Nyx hydrodynamical simulations with different combinations of underlying thermal parameters $T_0$, $\gamma$ and pressure smoothing scale $\lambda_P$ (see details in Oñorbe et al. 2017; Hiss et al. 2018) on a box size $L_{\text{box}} = 20$ Mpc/$h$ and $1024^3$ cells. The cosmological parameters used in the simulations were based on the results of the Planck mission (Planck Collaboration et al. 2014): $\Omega_m = 0.6808, \Omega_b = 0.3192, \sigma_8 = 0.826, \Omega_{\Lambda} = 0.04965, n_s = 0.9655$, and $h = 0.6704$. The parameters $T_0$ and $\gamma$ were extracted from the simulations by fitting the $T - \rho$ relation power-law to the distribution of gas cells as described

$^1$ thermal.joseonorbe.com
The mock spectra for calibration were prepared by adding the effects of resolution and noise to the simulated skewers. The quantities of both effects were selected to match the used spectra. We mimicked the instrumental resolution by convolving the skewers with a Gaussian with FWHM = 6 km s\(^{-1}\) and rebinning to 3 km s\(^{-1}\) pixels afterward.

In order to determine \(\lambda_p\), the cut-off in the power spectrum of the real-space Lyman-\(\alpha\) flux was fitted.

### 3.2 Thermal parameter grid

In this study, we used 23 skewers with a different combination of thermal parameters and pressure smoothing scale. The combinations of parameters \(T_0\), \(\gamma\) and \(\lambda_p\) are depicted in the Fig. 6. The grid of thermal parameters covers intervals: 6 200 < \(T_0\) < 21 200 [K] and 1.06 < \(\gamma\) < 1.91. In the case of the pressure smoothing scale, we chose range 46 < \(\lambda_p\) < 121 [kpc].

### 3.3 Modeling Noise, Resolution and Voigt Profile Fitting

The mock spectra for calibration were prepared by adding the effects of resolution and noise to the simulated skewers. The quantities of both effects were selected to match the used spectra. We mimicked the instrumental resolution by convolving the skewers with a Gaussian with FWHM = 6 km s\(^{-1}\) and rebinning to 3 km s\(^{-1}\) pixels afterward.
medians of bootstrap distributions. Using this approach, we obtained
the replacements. In the
points correspond to the median values of
log
datasets generated by bootstrapping. This is the same approach as we
i.e.
23 selected thermal models at the redshift
(0.1
2
0.2
0
72
55
11
08
20
11
0
0.6
0
8
0
8
0
8
5
72
55
11
08
20
11
0
0.6
0
8
0
8
5
72
55
11
08
20
11
0

thermal models. The results are shown in Fig.
8
pairs in
p(b0, Γ) with every point in the bootstrapped calibration PDFs
p(D, C) and
p(κ) from simulations using the Eqs. (12) and (13).
The resulting PDFs
p(T0, γ) for both studied redshift intervals are depicted in Fig. 9.
The medians of bootstrap distributions were used as the best estimates of the
T0
and
γ.
The derived parameter values for the redshift intervals
1.6 ≤ z ≤ 1.8 and 1.8 ≤ z ≤ 2.0 are listed in Tab 3.
The uncertainties correspond to the 16th and 84th percentiles of the probability distribution function
p(T0, γ).
The comparison of the results obtained in this study with previously published ones is shown in Fig. 10.

Schaye et al. (1999) showed that the effect of the S/N ratio on the results is negligible if its value is higher than ~ 20. However, the median of this parameter for the spectra used in this study is equal to 18. We tested the possibility that the lower value of
T0
and higher value of
γ
for mean value of redshift
z = 1.8 could be affected by the lower S/N ratio value, but our analysis showed that this effect is possible to neglect (see Appendix C).

We also considered the possibility that the obtained values of the calibration parameters could be influenced by using the calibration for the redshift
z = 1.8, whereas the centers of the redshift bins analysed in this study are 1.7 and 1.9. Based on the dependencies of the calibration parameters
C, D, and
κ on the redshift presented by Hiss et al. (2018) (Fig. 14 therein), we can conclude that changes of their values for the redshift differences
Δz = 0.1 are significantly lower than their uncertainties determined in this study, and this effect can be considered negligible.

The extended uncertainties of the derived parameters for the redshift range
1.6 ≤ z < 1.8 originate from the multimodal distribution
p(b0, Γ) (see Figs. 5). It is worth noting that the simulated
b − N\text{H}_{1}
istributions led to the unimodal solutions. Therefore, this behavior can be attributed to some systematics related with the used spectra, for which the cut-off fitting led to the artifacts. We assume that the effect is caused by the number of absorbers (~ 550) used for this redshift bin.

5.1 Comparison with previous studies

By comparing the values of
T0
and
γ obtained in this study with previously published ones (Fig. 10), it can be concluded that even there are some discrepancies, the results correspond to each other. An exception is the study by Boera et al. (2014), in which the temperature at the mean density assuming the value of
γ ∼ 1.3 is significantly higher for both mean redshifts
(z = 1.63 and 1.82) even compared

Table 3. Summary of the derived parameters for the studied redshift bins.

| Redshift range | b0 [km s\(^{-1}\)] | T0 [10\(^{5}\) K] | Γ | γ |
|---------------|-----------------|-----------------|---|---|
| (1.6, 1.8)    | 12.26\(^{+0.67}_{-0.49}\) | 8.69\(^{+0.05}_{-0.06}\) | 1.17\(^{+0.05}_{-0.06}\) | 1.55\(^{+0.20}_{-0.18}\) |
| (1.8, 2.0)    | 11.78\(^{+0.29}_{-0.83}\) | 7.51\(^{+0.01}_{-0.09}\) | 1.27\(^{+0.03}_{-0.02}\) | 1.72\(^{+0.11}_{-0.08}\) |

Figure 8. Calibrations of the
\log b_0
vs\ \log T_0
(upper panel) and
(Γ − 1)
(bottom panel) relations. The black lines correspond to the best linear fits to the points. The case, when the value of
b_0
corresponds to pure thermal broadening is depicted by the green dash line.

\[(\gamma - 1) = \kappa(\Gamma - 1),\]  

where
\[\kappa = D/B.\]

4.1 Calibration Using Simulations

To generate the calibrations between
b_0 − T_0
and
Γ − γ,
we used 23 selected thermal models at the redshift
z = 1.8. In this case, the cut-off fitting algorithm was used on simulated
b − N\text{H}_{1}
distributions, each of which was constructed using 120 mock spectra from all used thermal models. The results are shown in Fig. 8, where depicted points correspond to the median values of
b_0
and
Γ − 1
from 2 000 datasets generated by bootstrapping. This is the same approach as we used for the observational data.

To include the additional effects, such as various values of
λ_P
and using of the same value of the\ \log N\text{H}_{1}
for all models, we fitted Eqs. (12) and (13) to the 2 000 bootstrap realizations of the points in the\ \log (T_0) − \log (b_0)
and\ \log (γ) − (Γ − 1)
diagrams (see Fig. 8) with replacements. In the\ \log (b_0)
vs\ \log (T_0)
diagram, we also included the case when the value of
b_0
is caused purely by thermal broadening, i.e.\ b_0 = \sqrt{2k_BT_0/m_p},
where
k_B
is the Boltzmann constant and
m_P
is the proton mass.

The best fit values of the coefficients\ \kappa, D
and\ \kappa
correspond to the medians of bootstrap distributions. Using this approach, we obtained the values:\ C = 1.39\(^{+0.20}_{-0.24}\), D = 2.33\(^{+0.20}_{-0.17}\), and\ \kappa = 3.32\(^{+0.17}_{-0.17}\), where the uncertainties correspond to the 16th and 84th percentiles of the
p(D, C)
and
p(κ).

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to simulations. The differences can be attributed to the different methods used to estimate the values of $T_0$ and $\gamma$.

Only Schaye et al. (2000) studied the IGM in the redshift interval $1.85 \leq z \leq 2.09$ using the Voigt profile decomposition of the Ly-$\alpha$ forest into the set of individual absorption lines, as was used in this work. For the median value of the redshift $z = 1.96$, the authors determined value of $T_0 \sim 11\,000\,\text{K}$ and $\gamma = 1.4$, which differ from the ones obtained in our study for the redshift range $(1.8, 2.0)$. It is worth noting that Schaye et al. (2000) used the spectrum of only one quasar (Q100-264), the different value of log $N_{\text{HI},0} = 13$, and their median redshift value was slightly different from the one in this study ($z = 1.9$).

5.2 Comparison with models of the IGM thermal evolution

We compared the values of $T_0$ and $\gamma$ obtained in this study with results of various models of the IGM thermal evolution (see Fig. 10). Namely, the non-equilibrium simulation by Puchwein et al. (2015), the semi-analytical models by Upton Sanderbeck et al. (2016) where the He II reionization has and has not occurred, and hydrodynamical simulation by Oñorbe et al. (2017). The semi-analytical models by Upton Sanderbeck et al. (2016) were used only for qualitative comparison as these models depend on a number of parameters such as the ionizing background spectral index, the quasar spectral index, duration of the reionization, clumping etc. In addition, these models are not independent of observational data because the authors used the temperature measurements of Becker et al. (2011) and Boera et al. (2014) for constraining the model curves.

The comparison shows that the obtained temperatures at mean density for both redshift bins $(1.6, 1.8)$ and $(1.8, 2.0)$ are slightly lower than predicted by various models. In the case of redshift bin $(1.6, 1.8)$, the value of $T_0$ corresponds to the simulations within its error, although the uncertainty is considerably large.

The same conclusion can also be stated in the case of the power-law index, for which its value for the redshift bin $(1.6, 1.8)$ matches the non-equilibrium simulation of Puchwein et al. (2015), and within the error corresponds to all presented models. On the other hand, for the redshift bin $(1.8, 2.0)$, we obtained the value of the power-law index which is higher than the expected one $(\gamma \sim 1.6)$ resulting from the balance of photoheating and adiabatic cooling after all reionization events (Hui & Gnedin 1997; Upton Sanderbeck et al. 2016).

6 CONCLUSIONS

In this study, the sample of 35 quasar spectra was used for inferring parameters of the temperature-density relation in the IGM for the redshift interval $(1.6, 2.0)$. For this purpose, we used the approach that treats the Ly-$\alpha$ forest as a superposition of discrete absorption profiles. Based on the fitting, the $b - N_{\text{HI}}$ distributions were constructed, from which the position of thermal state sensitive cut-off was determined. We also calibrate our measurements using 23 combinations of thermal parameters and pressure smoothing scale from the THERMAL suite of hydrodynamical simulations. The main results can be summarized as follows:

- The obtained values correspond to the decreasing trend of the temperature at mean density predicted by the various models toward the lower redshifts.
- For the redshift interval $(1.6, 1.8)$, we obtained the power law index $\gamma = 1.55$. The value is close to 1.6, as expected by various models, and results from the balance of photoheating with adiabatic cooling after all reionization events. However, the determined value $\gamma = 1.72$ is higher for the redshift interval $(1.8, 2.0)$.
- Our determinations of $T_0$ and $\gamma$ at the lower redshift interval $(1.6, 2.0)$ indicate the completion of the reheating process associated to He II reionization.

ACKNOWLEDGEMENTS

This research is based on the use of the Keck Observatory Archive (KOA), which is operated by the W. M. Keck Observatory and the NASA Exoplanet Science Institute (NExScI), under contract with the National Aeronautics and Space Administration, and also on data products created from observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere. The authors would also like to thank Jose Oñorbe for fruitful discussion.

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.
Figure 10. Comparison of the results obtained in this study with previously published ones and various models. The black and red curves correspond to the semi-analytical models by Upton Sanderbeck et al. (2016) where the HeII reionization has and has not occurred, respectively. The blue and violet curves correspond to the non-equilibrium simulation by Puchwein et al. (2015) and the hydrodynamical simulation by Oñorbe et al. (2017), respectively.

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APPENDIX A: EFFECTS OF CONTINUUM MISPLACEMENT

In this section, we discuss the effect of continuum misplacement in used data. In the case of high-resolution, high S/N spectra, the continuum is fitted locally by connecting apparent absorption-free spectral intervals (McDonald et al. 2000; Kim et al. 2007). As was noted in Kim et al. (2007), this method is applicable for the redshift \(1.5 < z_{\text{em}} < 3.5\), where the continuum placement statistical uncertainty is of the order of a few percent.

As the continuum placement affects the corresponding optical depth of the spectral line, and consequently the line profile parameters, we address the effect by calculating the optical depth \(\tau\) in the line center as (Padmanabhan 2002)

\[
\tau_{\text{lc}}(\text{H}\ i) = 1.497 \times 10^{-15} \frac{N_f a_0}{b}, \tag{A1}
\]

where \(a_0 = 1215.67 \ \text{Å}, \ N_f = \text{cm}^{-2}\) and \(b = \text{km} \text{s}^{-1}\). For the calculation \(\tau_{\text{lc}}(\text{H}\ i)\) using Eq. (A1), we used the typical value of the Doppler parameter in our sample \(b = 13 \ \text{km} \text{s}^{-1}\) for spectral lines with various column densities. Then, we calculated the flux at line center according to equation \(F_{\text{lc}} = F_C \exp (-\tau_{\text{lc}}(\text{H}\ i)),\) where \(F_C\) was set up to unity, and the value of \(F_{\text{lc}}\) was shifted to mimic the effect of misplacement of the continuum. We assumed that our typical continuum uncertainty is \(\sim 5\%\). The final step was to calculate the corresponding column density by the reverse calculation with the fixed value of Doppler parameter.

The results showed that for the continuum shift of \(5\%\), the corresponding shift of \(\log N_{\text{H}\ i}\) is comparable to the VPFFIT uncertainty at \(\log N_{\text{H}\ i} \approx 12.5\) and exceeds it at lower values of column densities. From this result we can conclude that the effect of the continuum misplacement is possible to neglect within the cut-off fitting range used in this study.

APPENDIX B: MEAN FLUX RESCALING IN THE MODELS

As noted in Section 3.1, we rescaled the fluxes obtained from the simulations in order to match the observed mean flux \(\overline{F}\). In this work, we chose the value corresponding the mean flux evolution in Oñorbe et al. (2017), which is based on precise measurements by Fan et al. (2006); Becker et al. (2007); Kirkman et al. (2007); Faucher-Giguère et al. (2008); Becker & Bolton (2013). The \(\overline{F}\) value used in the case of simulations corresponds to the mean transmitted flux determined based on the KODIAQ/UVES spectra. The comparison is plotted in Fig. B1 together with the values determined from the studies of Kirkman et al. (2005) and Kim et al. (2007). We direct
Figure C1. Simulated $b - N_{\text{HI}}$ distributions at $z = 1.8$ with various S/N ratio values applied to lines of sight. The distributions were generated by Voigt profile fitting the same skewers as were used in the case of calibration process. The red points depict the distribution with S/N = 83 which corresponds to the highest S/N ratio value of used spectra. The black points correspond to the distribution with S/N = 20 characterizing the S/N ratio used in the case of the simulations. The thermal parameters used in these mock distributions are $\log(T_0) = 3.97$ [K], $y = 1.61$, and smoothing scale $\lambda_p = 74$ kpc.