AN ESTIMATION OF THE TEMPERATURE-DENSITY RELATION IN THE EARLY UNIVERSE

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Abstract: We present an independent estimate of the power-law index $(\gamma - 1)$ of the temperature-density relation $T \sim \rho^{\gamma-1}$ for the intergalactic medium at intermediate redshifts $z \sim 2 – 3$. The automatic program for analyzing Ly-alpha forest in the quasars spectra using Voigt profile fitting is developed. The analysis results in $(\gamma - 1) = 0.58 \pm 0.08$ at 68 per cent confidence level which is in a broad agreement with results of other authors. The proposed method can be easily extended to study large samples of archival quasar spectral data in an automatic regime.

Keywords: absorption lines, quasars, intergalactic medium.

Introduction

In the Standard Cosmology the primordial matter formed after the Big Bang was the hot optically thick fully ionized plasma. Three hundred thousand years later the temperature decreased enough and formation of atoms has started. Since that epoch the matter in the Universe had remained completely neutral until the first stars and galaxies began to produce ionizing radiation. As a consequence, at redshifts $z < 6$ the intergalactic hydrogen – the major constituent of the Universe – is almost completely ionized. The residual neutral fraction of the intergalactic medium (IGM) is easily detectable, e.g., as the Ly-alpha forest – the series of absorption lines in spectra of background quasars (QSOs). Majority of these lines correspond to Lyman series of neutral hydrogen HI (fig.1).

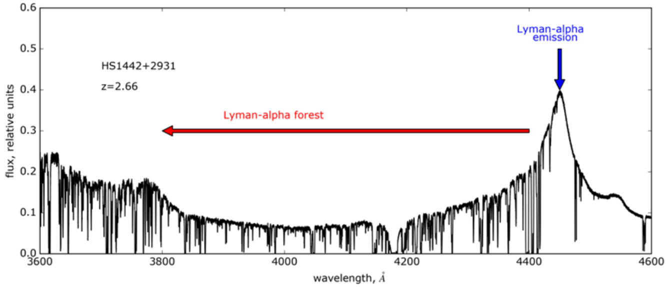

Fig.1. The spectrum of the QSO HS1442+2931 obtained using the HIRES spectrograph on the Keck telescope. The Ly-alpha forest is located in the spectral region bluewards the Ly-alpha emission line and consists of a large number of absorption lines, which correspond to IGM. To estimate the index of the IGM temperature-density power-law dependence we used Voigt profile fitting of these lines.

It is supposed [1] that the temperature and the density of the IGM are related by the power law

$$T = T_0 \left(\frac{\rho}{\bar{\rho}}\right)^{\gamma-1}, \qquad (1)$$

where T_0 is the temperature at the mean density $\bar{\rho}$. This form is set by the balance between an adiabatic cooling process due to cosmological expansion and photo-heating processes. It is expected that γ depends on z, i.e. the equation of state changes in course of the Universe evolution. Therefore, measurements of $\gamma(z)$ give insight into physical processes occurred in the early Universe.

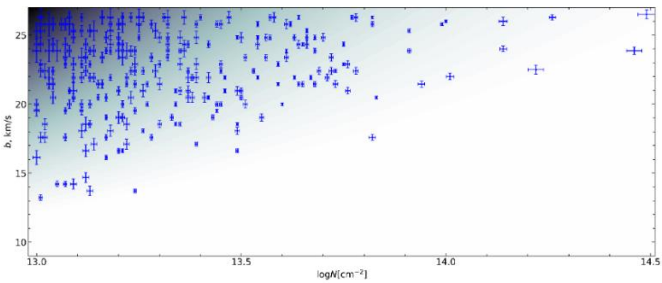

Fig.2. The gradient-filled area shows the best-fit $N - b$ distribution (with darker parts being the denser regions). Error crosses correspond to individual absorption lines found by the automatic search procedure in the selected quasar spectra, see text for details.

One of the few possible ways to infer $\gamma(z)$ is based on an analysis of the Ly-alpha forest, and, in particular, on the estimation of the column density N and the Doppler parameter b for each absorption line using Voigt profile [2–8]. The line parameters N and b depend on the density and the temperature of the absorption system as follows. Parameter b characterizes the width of the velocity distribution of neutral atoms in the system, and has contributions from thermal and turbulent motions. Under microturbulence assumption, these motions are independent and

$$b = \sqrt{\frac{2kT}{m} + b_{turb}^2}\,, \quad (2)$$

where b_{turb} is the width of the turbulent velocity distribution, k is the Boltzmann constant, and m is the mass of the absorber's atom. In case of negligible turbulence, $b_{turb} \to 0$, measured Doppler parameter, b, reflects the pure thermal broadening:

$$b \to b_{th} = \sqrt{\frac{2kT}{m}}. \quad (3)$$

In conditions of uniform ionizing radiation, the line column density N is related to the mass density ρ of the absorption system by the power law (e.g., [1–3]). In this case, eqs. (1) and (3) lead to the power-law dependence $b_{th} \sim N^{\Gamma-1}$, where approximately [2–3]

$$\gamma - 1 \approx 3(\Gamma - 1). \quad (4)$$

Therefore, an identification of the lower bound $b_{min}(N)$ of the $N - b$ distribution for a large sample of absorption systems allows to find the parameter $\gamma(z)$ in question. This method with some changes and improvements we use in this work.

Data

We selected 10 high resolution (~50000) quasar spectra with high signal-to-noise ratio (~50 – 100). The same sample was used in [2]. We downloaded 9 reduced 1D spectra from KODIAQ database (https://koa.ipac.caltech.edu/Datasets), and one spectrum, HS1442+2931, was reduced by hand.

Redshifts of the Ly-alpha emission peaks in these spectra lie in the range z = 2.5 – 2.9. In each quasar spectrum we scanned for the Ly-alpha forest lines between the Ly-alpha and the Ly-beta emission lines. Therefore the redshift interval of absorption systems studied in present work is z = 2.02 – 2.87. For each quasar we estimated an unabsorbed continuum level using B-spline interpolation.

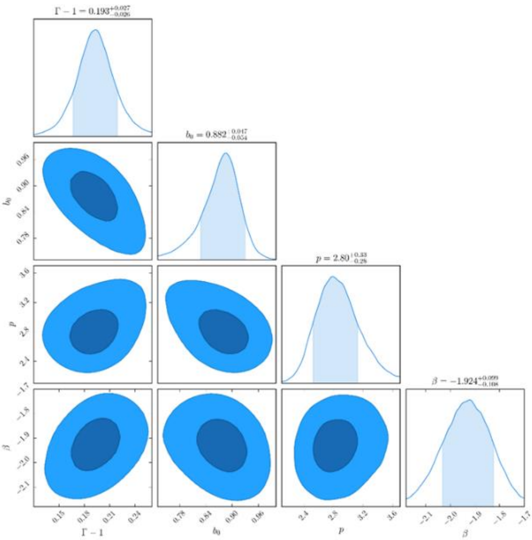

Fig.3. Marginalized posterior distributions of the parameters which specify the assumed b-N distribution. Blue and dark blue colors correspond to 0.683 (1 sigma) and 0.954 (2 sigma) confidence intervals, respectively.

Analysis and results

We used an automatic procedure for an analysis of the Ly-alpha forest. Instead of fitting every Ly-alpha forest line, we searched for these lines in the appropriate box in $N - b$ parameter space, near the expected $b_{min}(N)$. Assuming Gaussian statistical errors in the observed optical spectra, we used chi-square likelihood function to fit observed line profiles (consisting of ~30–40 spectral pixels) with modeled Voigt profile. Because the Ly-alpha forest is dense enough in the selected redshift range, some Ly-alpha forest lines blend with each other. To account for such blends we slightly modified likelihood function to remove blended pixels. To increase accuracy, we also added higher order Lyman series absorption lines associated with each Ly-alpha absorption line. The uncertainties on the obtained N and b values for each line were calculated via the Fisher matrix. The obtained (N, b) sample resulted from the automatic fitting and selection procedure is shown by error crosses in fig.2.

To proceed further, we assumed that the absorption systems are independently distributed over N and b_{turb} and both these distributions have power-law forms with indices β and p, respectively. For the N parameter this is a standard assumption (see, e.g., [9]). Using this assumption and eqs. (1–2) we performed the maximum likelihood estimate of the distribution parameters (β, p, Γ) and the normalization constant $b_0 = b_{th}(N = 10^{12} cm^{-2})$. The fitting was done employing the Markov Chain Monte Carlo (MCMC) simulations with the affine sampler *emcee* [10]. The probability density function was normalized in the box in the $N - b$ parameter space, where we searched for the Ly-alpha forest absorption features. The marginal posterior distributions of the fit parameters are shown in fig.3 and the theoretical $N - b$ distribution corresponding to the best-fit parameters is compared with the data sample in fig.2.

The main result of our analysis is the estimate $\gamma - 1 = 0.58 \pm 0.08$ at the 68 per cent confidence. Note that this is an average value corresponding to adopted redshift range of *z* = 2.02–2.87. In fig.4 we compare this result with available theoretical models and the results of similar analyses by other authors where various methods of the $b_{min}(N)$ estimation were used [2, 5–7].

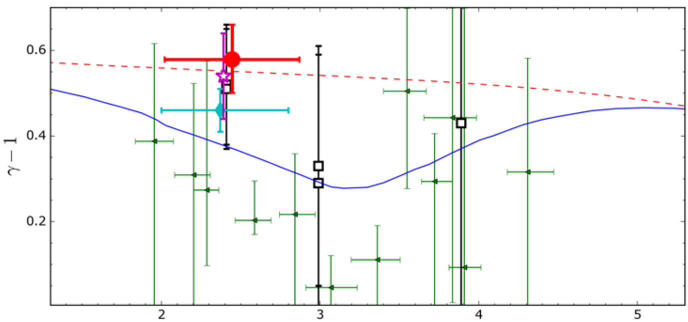

Fig.4. The evolution of $\gamma - 1$ with redshift, *z*. Solid and dashed lines show predictions of theoretical models with and without accounting for the HeII reionization, respectively [11]. Circle shows the result of the present work. Other measurements obtained by Voigt profile fitting of Ly-alpha forest are shown by triangles [4], squares [6], diamonds [2], and stars [5].

Summary

We developed the automatic procedure for fitting absorption lines over the Ly-alpha forest range in the spectra of QSOs using Voigt function. This procedure was applied to 10 spectra with high quality and resolution. We found that the power-law index of the IGM equation of state at z = 2.02–2.87 is $(\gamma - 1) = 0.58 \pm 0.08$ (68% confidence). Our result agrees (see fig.4) with the measurements done for the same spectra [2] and with other estimates made using the Ly-alpha forest line analysis via the Voigt function profile fitting [6]. An important advantage of our method is in a possibility to analyze large data samples in an automatic fashion. Therefore it can be applied to the quasar spectra in Keck and VLT archives without serious complications. This will allow us in a future to put robust constraints on the redshift dependence of the parameter $\gamma(z)$ and hence on the evolution of the IGM in the early Universe.

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