MEASURING THE TEMPERATURE OF THE INTERGALACTIC MEDIUM

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Abstract

Numerical simulations indicate that the smooth, photoionized intergalactic medium (IGM) responsible for the low column density Lyα forest follows a well defined temperature-density relation. We show that such an equation of state results in a cutoff in the distribution of line widths (b-parameters) as a function of column density (N) for the low column density absorption lines. This explains the existence of the lower envelope which is clearly seen in scatter plots of the b(N)-distribution in observed QSO spectra. The intercept and slope of this cutoff can be used to measure the equation of state of the IGM. Measuring the evolution of the equation of state with redshift will allow us to put tight constraints on the reionization history of the universe.

1 Introduction

Neutral hydrogen in the intergalactic medium (IGM) gives rise to a forest of Lyα absorption lines blueward of the Lyα emission line in quasar spectra. Hydrodynamic simulations of structure formation in a universe dominated by cold dark matter and including an ionizing background, show that the low column density (N < \(10^{14.5}\) cm\(^{-2}\)) Lyα forest at redshift z \(\gtrsim 2\) is produced by a smoothly varying IGM. For the low-density gas responsible for the Lyα forest, shock heating is not important and the gas follows a tight temperature-density relation. The competition between photoionization heating and adiabatic cooling results in a power-law ‘equation of state’ \(T = T_0(\rho/\bar{\rho})^{\gamma-1}\), which depends on cosmology and reionization history ².

The smoothly varying IGM gives rise to a fluctuating optical depth in redshift space. Many of the optical depth maxima can be fitted quite accurately with Voigt profiles. The distribution of line widths depends on the initial power spectrum, the peculiar velocity gradients around the density peaks and on the temperature of the IGM. However, there is a lower limit to how narrow the absorption lines can be. Indeed, the optical depth will be smoothed on a scale determined by three processes: thermal broadening, baryon (Jeans) smoothing and possibly instrumental, or in the case of simulations, numerical resolution. The first two depend on the thermal state of the gas. While for high-resolution observations (echelle spectroscopy) the effective smoothing scale is not determined by the instrumental resolution, numerical resolution has in fact been the limiting factor in many simulations (see ³ for a discussion).

Scatter plots of the b(N)-distribution have been published for many observed QSO spectra ⁴,⁵,⁶,⁷,⁸. These plots show a clear cutoff at low b-parameters, which increases slightly with
Figure 1: The $b(N)$-distribution for 800 random lines from models with $\log T_0 = 4.20$ (a) and $\log T_0 = 3.83$ (b) respectively, at $z = 3$. The position of each line is indicated by a cross. Errors are not displayed. The dashed line is the cutoff for the lines plotted in panel (a) over the range $10^{12.5}\text{cm}^{-2} \leq N \leq 10^{14.5}\text{cm}^{-2}$.

column density. However, this cutoff is not absolute, there are some narrow lines, especially at low column densities. Lu et al. [6] and Kirkman & Tytler [5] use Monte Carlo simulations to show that many of these lines are caused by line blending and noise in the data. Some contamination from unidentified metal lines is also expected. A lower envelope which increases with column density has also been seen in numerical simulations [9].

In this contribution we shall demonstrate that the cutoff in the $b(N)$-distribution is determined by the equation of state of the low-density gas and can therefore be used to measure the equation of state of the IGM. This work will be more fully described and discussed in a forthcoming publication [7].

2 Results

In Fig. 1a we plot the $b(N)$-distribution for 800 random absorption lines taken from multi-component Voigt profile fits of spectra at redshift $z = 3$, generated from one of our simulated models. A cutoff at low $b$-values, which increases with column density, can clearly be seen. As in the observations, there are some very narrow lines, which occur in blends. These unphysically narrow lines make determining the cutoff in an objective manner nontrivial. We developed an iterative procedure for fitting a power-law, $b = b_0(N/N_0)^{\Gamma-1}$, to the $b(N)$-cutoff over a certain column density range ($10^{12.5}\text{cm}^{-2} \leq N \leq 10^{14.5}\text{cm}^{-2}$ at $z = 3$) which is insensitive to these narrow lines.

The $b(N)$-distribution for a colder ($\log T_0 = 3.83$ vs. $\log T_0 = 4.20$) model is plotted in Fig. 1b. Clearly, the distribution cuts off at lower $b$-values. Let us assume that the absence of lines with low $b$-values is due to the fact that there is a minimum line width set by the thermal state of the gas through the thermal broadening and/or baryon smoothing scales. Since the temperature of the low-density gas responsible for the Ly$\alpha$ forest increases with density, we expect the minimum $b$-value to increase with column density, provided that the column density correlates with the density of the absorber.

To see whether this picture is correct, we need to investigate the relation between the Voigt profile parameters $N$ and $b$, and the density and temperature of the absorbing gas respectively.
Figure 2: The gas density at the line centres as a function of neutral hydrogen column density. Data points correspond to the lines plotted in Fig. 1a.

Figure 3: The temperature at the line centres as a function of the $b$-parameter. The left panel contains all lines plotted in Fig. 1a. In the right panel only those lines are plotted which have $b$-parameters within one mean absolute deviation of the power-law fit to the $b(N)$-cutoff plotted as the dashed line in Fig. 1a. The dashed line corresponds to the thermal width, $b = (2k_BT/m_p)^{1/2}$.

From Fig. 2, which shows the gas density as a function of column density for the absorption lines plotted in Fig. 1a, it can be seen that these two quantities are tightly correlated.

The temperature is plotted against the $b$-parameter in Fig. 3a. The result is a scatter plot with no apparent correlation. This is not surprising since many absorbers will be intrinsically broader than the local thermal broadening scale. In order to test whether the cutoff in the $b(N)$-distribution is a consequence of the existence of a minimum line width set by the thermal state of the gas, we need to look for a correlation between the temperature and $b$-parameters of the lines near the cutoff. Fig. 3b shows that these lines do indeed display a tight correlation. The dashed line corresponds to the thermal width, $b = (2k_BT/m_p)^{1/2}$, where $m_p$ is the mass of a proton and $k_B$ is the Boltzmann constant. Lines corresponding to density peaks whose width in velocity space is much smaller than the thermal broadening width, have Voigt profiles with this $b$-parameter.

Figs. 2 and 3b suggest that the cutoff in the $b(N)$-distribution should be strongly correlated with the equation of state of the absorbing gas. The objective is to establish the relations
Figure 4: The intercept of the $b(N)$-cutoff as a function of the temperature at mean density (left panel) and the slope as a function of the index of the power-law equation of state (right panel), for redshift $z = 3$. The error bars enclose 68% confidence intervals around the medians, as determined from 500 sets of 300 random lines. The dashed lines are the maximum likelihood fits.

between the cutoff parameters and the equation of state using simulations. These relations turn out to be unaffected by systematics like changes in cosmology (for a fixed equation of state) [7] and can thus be used to measure the equation of state of the IGM using the cutoff in the observed $b(N)$-distribution.

The amplitudes of the power-law fits to the cutoff and the equation of state are plotted against each other in the left panel of Fig. [I]. The error bars, which indicate the dispersion in the cutoff of sets of 300 lines (typical for $z = 3$), are small compared to the differences between the models. This means that measuring the cutoff in a single QSO spectrum can provide significant constraints on theoretical models (at $z = 3$, physically reasonable ranges for the parameters of the equation of state are $10^{3.0} K < T_0 < 10^{4.5} K$ and $1.2 < \gamma < 1.7$ [3, 4]). The slope of the cutoff, $\Gamma - 1$, is plotted against $\gamma$ in the right panel of Fig. [I]. The dispersion in the slope of the cutoff for a fixed equation of state is comparable to the difference between the models. The weak dependence of $\Gamma$ on $\gamma$ and the large spread in the measured $\Gamma$ will make it difficult to put tight constraints on the slope of the equation of state.

References

[1] Hu E.M., Kim T., Cowie L.L., Songaila A., Rauch M., 1995, *Astron. J.* 110, 1526
[2] Hui L., Gnedin N., 1997, *MNRAS* 292, 27
[3] Hui L., Gnedin N., Zhang, Y., 1997, *MNRAS* 486, 599
[4] Kim T., Hu E.M., Cowie L.L., Songaila A., 1997, *Astron. J.* 114, 1
[5] Kirkman D., Tytler, D., 1997, *Astrophys. J.* 484, 672
[6] Lu L., Sargent W.L.W., Womble D.S., Takada-Hidai M., 1996, *Astrophys. J.* 472, 509
[7] Schaye, J., Theuns, T., Leonard, A., Efstathiou, G., 1999, *submitted to MNRAS*
[8] Theuns T., Leonard A., Efstathiou G., Pearce F.R., Thomas P.A., 1998, *MNRAS* 301, 478
[9] Zhang Y., Anninos P., Norman M.L., Meiksin A., 1997, *Astrophys. J.* 485, 496