Detecting He\textsc{ii} reionization from a sudden injection of entropy in the intergalactic medium

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Abstract. The temperature of the low-density intergalactic medium is set by the balance between adiabatic cooling resulting from the expansion of the universe, and photo-heating by the UV-background. A sudden injection of entropy from the reionization will increase the temperature of the gas, leading to a broadening of the hydrogen Lyman-\(\alpha\) absorption lines produced in the IGM, and observed in the spectra of background quasars. We present a method based on wavelets to characterise objectively the line widths of such absorption lines. We use high resolution hydrodynamical simulations to demonstrate that the algorithm can detect changes in temperature of order of 50 per cent on scales $\geq 5000$ km s$^{-1}$. We apply the method to a UVES/VLT spectrum of quasar 0055–269 ($z_{\text{em}} = 3.7$) and detect at the 99 per cent confidence level a sudden increase in temperature below redshift $z \sim 3.3$, which we interpret as evidence for He\textsc{ii} reionization.

1 Introduction

The intergalactic medium (IGM) can be observed in the spectra of distant quasars through resonant absorption in the hydrogen Lyman-\(\alpha\) transition \textsuperscript{[1]}. The absence of strong absorption throughout the spectrum (Gunn-Peterson trough) indicates that the IGM is very highly ionised, $\rho_{\text{HI}}/\rho_{\text{H}} \sim 10^{-4}$ below redshifts $z \sim 6$, but the nature of the first ionising sources remains uncertain.

If the sources responsible for reionizing H\textsc{i} are sufficiently hard, then He\textsc{ii} will be reionized at the same time. However, if for example galaxies were the main contributor to the UV-background, then He\textsc{ii} reionization may be significantly delayed until a population of harder sources appears. The large fluctuations in the He\textsc{ii} optical depth observed with STIS and FUSE \textsuperscript{[2]} suggest He\textsc{ii} reionization occurs late, around $z \sim 3$. There is supporting evidence from the hardening of the UV-background, as deduced from metal line ratios although these results remain controversial \textsuperscript{[3]}.

*Based on the data obtained from the OPC program 65.O-0296A (P.I. S. D’Odorico) at the VLT/Kueyen telescope, ESO, Paranal, Chile.
An independent approach is to study the temperature of the IGM. Photo-heating and adiabatic expansion introduce a tight density-temperature relation \( T = T_0 (\rho / \langle \rho \rangle)^{\gamma - 1} \), for the low density IGM responsible for producing the Lyman-\( \alpha \) forest. A sudden injection of entropy resulting from reionization will increase \( T_0 \) and make the gas nearly isothermal, \( \gamma \sim 1 \). Detecting reionization through a sudden entropy increase has the advantage that one determines the epoch at which a significant fraction of the volume of the universe is overrun by the ionization front.

Schaye et al. used hydrodynamical simulations to demonstrate that the density-temperature relation introduces a cut-off in the scatter plot of column density \( N_{\text{HI}} \) versus line width \( b \). They used a set of many high resolution simulations to calibrate the relation between the position of the cut-off and \( (T_0, \gamma) \). Applying the calibration to the cut-off measured in ten high-resolution spectra, they found evidence for a rise in \( T_0 \) around a redshift \( z \sim 3 \), and an associated dip in \( \gamma \), which they associated with He\( \text{II} \) reionization. Ricotti, Gnedin & Shull applied a similar technique, but calibrated with pseudo hydrodynamical simulations, to published line lists, and found a similar temperature increase, although their error bars are large and their result is consistent with a non-evolving \( T_0 \) as well. Bryan & Machacek also found evidence for a high value of \( T_0 \), but McDonald et al. did not find an increase in \( T_0 \) around \( z = 3.3 \), although they used largely the same data as Schaye et al.

Zaldarriaga applied a wavelet analysis similar to the one discussed here to look for temperature changes in the spectrum of QSO 1422+231 which might be a relic from reionization, and constrained them to be smaller than a factor of 2.5.

2 Wavelet analysis

A discrete wavelet is a localised function with a finite bandwidth. This makes wavelets useful for characterising line widths in a spectrum, since the amplitude of the wavelet will be related to the width of the line, and the position of the wavelet to the position of the line. The decomposition is moreover unique, for a given wavelet basis.

Theuns & Zaroubi used the Daubechies 20 wavelet to characterise temperature fluctuations in simulated Lyman-\( \alpha \) spectra. They demonstrated how the wavelet amplitudes are large when the gas is cold and the lines narrow, and vice versa. They also showed how the cumulative distribution of wavelet amplitudes can be used to characterise the gas temperature, and to judge whether two stretches of spectrum have different temperatures or not. Here, we have used \( \Delta \), the maximum difference between the cumulative distribution of a stretch of spectrum, and the distribution for the spectrum as a whole, as a measure of how much \( T_0 \) for a stretch, differs from \( \langle T_0 \rangle \).

We have extended this method to attach a statistical significance to differences in cumulative distributions. Given a line list, we construct mock spectra
by scrambling the lines, thereby producing a spectrum where the lines have the same shapes as in the original spectrum, but any correlation in line widths that might result from temperature variations along the spectrum has been removed. We can now attach a statistical level of significance for the correlation between line widths – and hence the temperature of the gas – by comparing the statistics of the original spectrum with the scrambled one.

In our simulation, we chose the photo-ionization rates for Hydrogen and Helium such that H\textsubscript{i} and He\textsubscript{i} reionize around redshift $z \sim 7$ but He\textsubscript{ii} reionization is delayed until $z \sim 3.4$. In order to investigate the effect of different temperatures, we impose a power law equation of state, $T = T_0 \langle \rho / \langle \rho \rangle \rangle ^\gamma - 1$, on the simulation output before computing mock spectra. We have used $(T_0, \gamma) = (1.5 \times 10^4 K, 5/3)$ and $(2.2 \times 10^4 K, 5/3)$. These spectra are made to look like real data as much as possible, by adding photon and read-out noise, and broadening the lines with the instrumental profile of the spectrograph. Voigt profiles are fitted to the absorption lines with the same programme as used to analyse the data.

3 Results

Our results are shown in Fig. 1. The dot--dashed line (right hand scale) is the maximum difference between the cumulative distribution of wavelet coefficients.
for a window of size 8000 km s$^{-1}$ at redshift $z$, and the spectrum as a whole. Histogram (left hand scale) is the significance (in %) for unusually large values of $|\Delta|$, obtained from comparison with spectra constructed from randomised line lists. Negative values indicate gas colder than average, and vice versa for positive values. In the simulated spectrum (top panel), the first and second halves of the spectrum have $T_0 = 2.2 \times 10^4$K and $1.5 \times 10^4$K respectively. The wavelet statistic $\Delta$ detects this imposed jump, as can be seen from the sudden change in the sign of $\Delta$. The significance of the change is computed to be $\geq 99.5$ per cent. The bottom panel applies the analysis to the spectrum of QSO 0055–269. We detect a sudden change in the value of $\Delta$ around $z \sim 3.3$, significant at the $\geq 99.5$ per cent. Note that no simulations are used to compute the level of significance: the method described here is solely based on the line list.

We note that the high redshift gas is colder than the lower redshift gas. This is opposite to what one would expect from photo-heating in the optically thin limit, in which case the IGM will smoothly cool down. Therefore we suggest this sudden temperature increase is due to HeII reionization at redshift $\sim 3.3$.

**Acknowledgements.** We thank S. D’Odorico, S. Cristiani, E. Giallongo, A. Fontana and S. Savaglio for allowing us to use the UVES data prior to publication. TT thanks PPARC for the award of a post-doctoral position. This work has been supported by the ‘Formation and Evolution of Galaxies’ and ‘Physics of the Intergalactic Medium’ networks set up by the European Commission. Research conducted in cooperation with Silicon Graphics/Cray Research utilising the Origin 2000 super computer at the Department for Applied Mathematics and Theoretical Physics, Cambridge.

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