Constraining reionization using the thermal history of the baryons

Joop Schaye
Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK

Tom Theuns
Max-Planck-Institut für Astrophysik, Postfach 1523, 85740 Garching, Germany

Michael Rauch
European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany

George Efstathiou
Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK

Wallace L. W. Sargent
Astronomy Department, California Institute of Technology, Pasadena, CA 91125, USA

Abstract. The thermal evolution of the intergalactic medium (IGM) depends on the reionization history of the universe. Numerical simulations indicate that the low density IGM, which is responsible for the low column density Ly$\alpha$ forest, follows a well defined temperature-density relation. This results in a cut-off in the distribution of line widths as a function of column density. We use hydrodynamic simulations to calibrate the relation between the cut-off and the temperature-density relation and apply this relation to Keck spectra spanning a redshift range $z = 2-4.5$. We find that the temperature peaks at $z \sim 3$ and interpret this as evidence for reheating due to the reionization of helium.

1. Introduction

Quasars have provided us with a unique probe of the high redshift universe. These bright point sources shine like a flashlight through space, revealing the presence of baryonic matter through the light it absorbs. Thus every quasar spectrum contains a one-dimensional map of the distribution of matter along the line of sight. The extraordinary quality of the spectra obtainable with the HIRES spectrograph on the Keck telescope, enables us to extract the wealth of information that has been collected by the quasar's light along its journey through space and time. Computer simulations of structure formation have
been remarkably successful in reproducing these observations. They show that
the physics governing the high redshift intergalactic medium (IGM), which is
responsible for the low column density absorption lines (the so-called Ly\(\alpha\)
forest) is relatively simple. The IGM, which contains most of the baryons in the
universe, is photoionized and photoheated by the collective UV radiation from
young stars and quasars. On large scales its dynamics are determined by the
gravitational field of the dark matter, while on small scales gas pressure is im-
portant. The availability of superb data and a detailed physical model, have
made the Ly\(\alpha\) forest into a powerful probe of the high-redshift universe.

Since shock heating is unimportant in the low-density IGM, most of the gas
follows a simple temperature-density relation which is the result of the interplay
of photoionization heating and adiabatic cooling due to the expansion of the
universe. For densities around the cosmic mean, this relation is well-described
by a power-law, \(T = T_0(\rho/\bar{\rho})^{\gamma - 1}\) (Hui & Gnedin 1997). At reionization the gas
is reheated, resulting in an increase in \(T_0\) and a decrease in \(\gamma\) (provided that the
gas is reionized on a timescale short compared to the Hubble time). In ionization
equilibrium, \(T_0\) decreases and the slope of the effective equation of state steepens
(i.e. \(\gamma\) increases). However, because the timescale for recombination is long, the
gas retains some memory of how and when it was reionized (Miralda-Escudé &
Rees 1994).

The distribution of line widths (\(b\)-parameters) depends on various mecha-
nisms. Thermal motions of the hydrogen atoms broaden the HI absorption lines
and other processes, such as the differential Hubble flow across the absorbing
structure and bulk flows, also contribute to the line widths. However, the mini-
mum line width is set by the temperature of the gas, which in turn depends on
the density. A standard way of analyzing Ly\(\alpha\) forest spectra is by decomposing
them into a set of Voigt profiles. Since the minimum line width (\(b\)-parameter)
depends on the temperature, and since column density (\(N\)) correlates strongly
with physical density, there is a cut-off in the \(b(N)\) distribution which traces
the effective equation of state of the IGM (Schaye et al. 1999; Ricotti, Gnedin
& Shull 2000; Bryan & Machacek 2000). We have used this relation to measure
the thermal evolution of the IGM from a set of nine Ly\(\alpha\) quasar absorption line
spectra.

This work is more fully described and discussed in a forthcoming publication
(Schaye et al. 2000).

2. Method

We have measured the \(b(N)\) cut-off for a set of nine high-quality Ly\(\alpha\) forest
spectra, spanning the redshift range 2.0–4.5, eight of which were taken with the
HIRES spectrograph of the Keck telescope. We used hydrodynamic simulations
to calibrate the relations between the \(b(N)\) cut-off and the temperature-density
relation. Except for the two lowest redshift quasars, the Ly\(\alpha\) forest spectra were
split in two in order to take into account the significant redshift evolution (\(\Delta z \sim
0.5\)) and signal-to-noise variation across a single spectrum. The calibration was
done separately for each half of each observed spectrum. The synthetic spectra
were processed to give them identical characteristics (resolution, pixel size, noise
properties, mean absorption) as the real data. The same Voigt profile fitting
3. Results and discussion

The measured evolution of the temperature at the mean density and the slope of the effective equation of state are plotted in Figure 1. From $z \sim 3.5$ to $z \sim 3.0$, $T_0$ increases and the gas becomes close to isothermal ($\gamma \sim 1.0$). This behavior differs drastically from that predicted by models in which helium is fully reionized at higher redshift. For example, the solid lines correspond to a simulation that uses a uniform metagalactic UV-background from quasars as computed by Haardt & Madau (1996) and which assumes the gas to be optically thin. In this simulation, both hydrogen and helium are fully reionized by $z \sim 4.5$ and the temperature of the IGM declines slowly as the universe expands. Such a model can clearly not account for the peak in the temperature at $z \sim 3$ (reduced $\chi^2$ for the solid curves are 6.9 for $T_0$ and 3.6 for $\gamma$). Instead, we associate the peak in $T_0$ and the low value of $\gamma$ with reheating due to the second reionization of helium ($\text{He}^\text{II} \rightarrow \text{He}^\text{III}$). This interpretation is supported by measurements of the SiIV/CIV ratio (Songaila 1998, but see also Boksenberg, Rauch, & Sargent 1998 and Giroux & Shull 1997) and direct measurements of the HeII opacity (Heap et al. 2000 and references therein).

The dashed lines in Figure 1 are for a model that was designed to fit the data (reduced $\chi^2$ is 0.24 for $T_0$ and 1.38 for $\gamma$). In this simulation, which has a much softer UV-background at high redshift, HeII reionizes at $z \sim 3.2$. Before reionization, when the gas is optically thick to ionizing photons, the mean energy per photoionization is much higher than in the optically thin limit (Abel & Haehnelt 1999). We have approximated this effect in this simulation by en-
hancing the photoheating rates during reionization, so raising the temperature of the IGM.

Since the simulation assumes a uniform ionizing background, the temperature has to increase abruptly (i.e., much faster than the gas can recombine) in order to make $\gamma$ as small as observed. In reality, the low-density gas may be reionized by harder photons, which will be the first ionizing photons to escape from the dense regions surrounding the sources. This would lead to a larger temperature increase in the more dilute, cooler regions, resulting in a decrease of $\gamma$ even for a more gradual reionization. Furthermore, although reionization may proceed fast locally (as in our small simulation box), it may be patchy and take some time to complete. Hence the steep temperature jump indicated by the dashed line, although compatible with the data, should be regarded as illustrative only. The globally averaged $T_0$ could well increase more gradually which would also be consistent with the data. More data at $z \gtrsim 3$ is needed to determine whether the temperature rise is sharp or gradual. On the theoretical side, more realistic models should include radiative transfer effects, which are important during reionization.

Together with measurements of the He II opacity, which probe the ionization state in the voids, the thermal history of the IGM provides important constraints on models of helium reionization. Furthermore, the temperature of the IGM before the onset of helium reionization can be used to constrain the redshift of hydrogen reionization, which marks the end of the dark ages of cosmic history.

Acknowledgments. We are grateful to Bob Carswell and Sara Ellison for giving us permission to use their spectra of the quasars Q1100−264 and APM 08279+5255 respectively.

References

Abel, T., & Haehnelt, M. G. 1999, ApJ, 520, L13
Boksenberg, A., Sargent, W. L. W., & Rauch, M. 1998, preprint (astro-ph/9810502)
Bryan, G. L., & Machacek, M. E. 2000, ApJ, submitted (astro-ph/9906459)
Giroux, M. L., & Shull, J. M. 1997, AJ, 113, 1505
Heap, S. R., Williger, G. M., Smette, A., Hubeny, I., Sahu, M., Jenkins, E. B., Tripp, T. M. & Winkler, J. N. 2000, ApJ, in press (astro-ph/9812429)
Haardt, F., & Madau, P. 1996, ApJ, 461, 20
Hui, L. & Gnedin, N. Y. 1997, MNRAS, 292, 27
Miralda-Escudé, J., & Rees, M. J. 1994, MNRAS, 266, 343
Ricotti, M., Gnedin, N. Y., & Shull, J. M. 2000, ApJ, in press (astro-ph/9906413)
Schaye, J., Theuns, T., Leonard, A., & Efstathiou, G. 1999, MNRAS, 310, 57
Schaye, J., Theuns, T., Rauch, M., Efstathiou, G., & Sargent, W. L. W. 2000, MNRAS, submitted (astro-ph/9912432)
Songaila, A. 1998, AJ, 115, 2184
Webb, J. K. 1987, Ph.D. thesis, Univ. Cambridge