Reionization signatures in QSOs and GRBs absorption spectra

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In collaboration with:
**QSO spectra at high redshift**

$$\tau_{GP}(z) = 4.9 \times 10^5 \left( \frac{\Omega_m h^2}{0.13} \right)^{-1/2} \left( \frac{\Omega_b h^2}{0.02} \right) x_{HI} \left( \frac{1+z}{7} \right)^{3/2}$$

Fan et al. 2005

**What can we learn from these observables?**

Becker et al. 2003
Simulating the Ly$\alpha$ forest

$F(\nu) = e^{-\tau(\nu)}$  

optical depth at the Ly$\alpha$ transition

$\tau(\nu) = \int \sigma_{\text{Ly}\alpha} n_{\text{HI}} dl$

Neutral hydrogen distribution

Baryonic density field  

IGM ionization state

Log-Normal model  

Coles & Jones  
(1991)

Reionization model  

Choudhury & Ferrara  
(2005/2006)
Reionization models

**EARLY REIONIZATION (ERM)**

**LATE REIONIZATION (LRM)**

Data from McDonald & Miralda-Escude’(2001); Bolton et al. (2005/2007); Fan et al. (2006)
Simulated spectra

\[ z = 5.7 - 6.3 \]
Largest gap width distribution

Observations vs Simulations

Low Redshift ($z_{em} < 6$)

High Redshift ($z_{em} > 6$)

$\bar{z} = 5.3$

$\bar{z} = 5.6$

$W_{max} (\text{Å})$

$W_{max} (\text{Å})$
Largest gap width distribution

Observations vs Simulations

Low Redshift ($z_{em} < 6$)

High Redshift ($z_{em} > 6$)

$\bar{z} = 5.3$

$\bar{z} = 5.6$

$z_{HR} = \frac{z_{3.5}}{\frac{6.5}{3.5}}$
Largest gap width distribution

Observations vs Simulations

Low Redshift ($z_{em} < 6$)

High Redshift ($z_{em} > 6$)

$\bar{z} = 5.3$

$x_{HI} \approx 4 \times 10^{-5}$

$\bar{z} = 5.6$

$x_{HI} \approx 6 \times 10^{-5}$

$x_{HI} < 0.36 @ z = 6.3$

Simulated spectra

$z = 5.7 \div 6.3$

PEAKS

ERM

LRM

$\lambda_{RF}$

(flux $q_{1D}=0.89$)
Transmissivity windows

What is the origin of the peaks?

Cosmic underdense regions

\[ \Delta \equiv \frac{\rho}{\bar{\rho}} \]

\[ \Delta \approx 1 \]

\[ \Delta \approx 0.1 \]
Largest peak width distribution

Observations vs Simulations

Low Redshift ($z_{em} < 6$) vs High Redshift ($z_{em} > 6$)

$P_{max}$ (Å) vs $f_{los}$
Transverse proximity effect: observations

RD J1148+5252

$R_\perp = 0.7$ Mpc

$M_B = -24.3$
Transverse proximity effect: observations

RD J1148+5252

$R_\perp = 0.7$ Mpc

$M_B = -24.3$

Mahabal et al. (2005)  
Fan et al. (2006)  
QSO1  
QSO2  
RD J1148+5252

Yu (2005)  
Shapiro et al. (2006)  
White et al. (2003)  
Wyithe et al. (2005)
Transverse proximity effect: simulations

Peaks origin:

Underdense Regions (case A)

Texture simulation of an Underdense Cloud (A) and an HII Region (B) with different radii. The spectrum of the peaks is shown on the right.
**Transverse proximity effect:** observations vs simulations

\[ R = 0 \quad R_τ \approx 2\text{Mpc} \]

\[ t_Q > \frac{R_τ - R_⊥}{c} \approx 11\text{Myr} \]
Additional lighthouses: GRBs

* Afterglow spectra follow a power-law (easier continuum determination).

* GRBs are soon expected to be found at redshifts higher than QSOs ones.
[GRB 050904 @ z=6.29 (Kawai et al. 2006)]
Observed GRBs absorption spectrum: GRB050904

\[ z_{GRB} = 6.3 \]

Kawai et al. (2006)
Observed GRBs absorption spectrum: GRB050904

$z_{GRB} = 6.3$  

Kawai et al. (2006)
Observed GRBs absorption spectrum: GRB050904

$z_{GRB} = 6.3$  

Kawai et al. (2006)
The \textbf{ERM} is twice more probable wrt the \textbf{LRM}

The gap sizes are consistent with $x_{HI}=7 \times 10^{-5}$. 
Largest gap probability isocontours: QSOs

\[ \text{Work in progress} \]

\[ z_{em} = 6.42 \quad 10\% \quad 10\% \quad 30\% \quad 20\% \quad 30\% \quad 20\% \]

\[ z_{em} = 6.28 \quad 10\% \quad 10\% \quad 30\% \quad 20\% \quad 30\% \quad 20\% \]

J1148+5251

J1030+0524
Conclusions

Epoch of reionization $z \sim 6$

(See also Becker et al. 2007)

The analysis of QSOs and GRBs absorption spectra favors a highly ionized IGM at $z \sim 6$, suggesting an earlier epoch of reionization.