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Constraining cosmic reionization with quasar, gamma ray burst, and Lyα emitter observations

S. Gallerani[1], A. Ferrara[2], T. Roy Choudhury[3], X. Fan[4], R. Salvaterra[5], P. Dayal[6]

[1] INAF-Osservatorio Astronomico di Roma, via di Frascati 33, 00040 Monte Porzio Catone, Italy, e-mail: `gallerani@oa-roma.inaf.it`
[2] Scuola Normale Superiore, Piazza dei Cavalieri 7, 56126 Pisa, Italy
[3] Harish-Chandra Research Institute, Chhatnag Road, Jhusi, Allahabad 211 019, India
[4] Steward Observatory, 933 N. Cherry Ave, Tucson, AZ 85721-0065, US
[5] INAF-Osservatorio Astronomico di Brera, via E. Bianchi 46, 23807 Merate (LC), Italy
[6] Scuola Internazionale Superiore di Studi Avanzati, via Beirut 2-4, 34151 Trieste, Italy

Abstract. We investigate the cosmic reionization history by comparing semi-analytical models of the Lyα forest with observations of high-z quasars and gamma ray bursts absorption spectra. In order to constrain the reionization epoch $z_{\rm rei}$, we consider two physically motivated scenarios in which reionization ends either early (ERM, $z_{\rm rei} \gtrsim 7$) or late (LRM, $z_{\rm rei} \approx 6$). We analyze the transmitted flux in a sample of 17 QSOs spectra at $5.7 \leq z_{\rm em} \leq 6.4$ and in the spectrum of the GRB 050904 at $z = 6.3$, studying the wide dark portions (gaps) in the observed absorption spectra. By comparing the statistics of these spectral features with our models, we conclude that current observational data do not require any sudden change in the ionization state of the IGM at $z \approx 6$, favouring indeed a highly ionized Universe at these epochs, as predicted by the ERM. Moreover, we test the predictions of this model through Lyα emitters observations, finding that the ERM provide a good fit to the evolution of the luminosity function of Lyα emitting galaxies in the redshift range $z = 5.7 - 6.5$. The overall result points towards an extended reionization process which starts at $z \gtrsim 11$ and completes at $z_{\rm rei} \gtrsim 7$, in agreement with the recent WMAP5 data.

Key words. cosmology: large scale structure - intergalactic medium - quasars: absorption lines - gamma-ray: bursts - galaxies: high redshift - luminosity function

1. Introduction

In the last few years a possible tension has been identified between WMAP5 data (Dunkley et al. 2009) and SDSS observations of quasar (QSO) absorption spectra (Fan et al. 2006), the former being consistent with an epoch of reionization $z_{\rm rei} \approx 11$, the latter suggesting $z_{\rm rei} \approx 6$. Long Gamma Ray Bursts (GRB) may constitute a complementary way to study the reionization process, possibly probing $z > 6$ (Tagliaferri et al. 2005; Greiner et al. 2009; Salvaterra et al. 2009). Moreover, an increasing number of Lyman Alpha Emitters (LAE) are routinely found at $z > 6$ (Stark et al. 2007).

The ultraviolet radiation emitted by a QSO/GRB can suffer resonant Lyα scattering as it propagates through the intergalactic neu-

Send offprint requests to: S. Gallerani

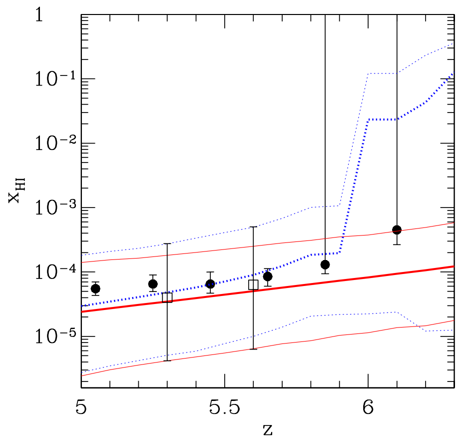

Fig. 1. Evolution of the neutral hydrogen fraction. Thick red solid (blue dotted) lines represent average results over 100 LOS for the ERM (LRM), while the thin lines denote the upper and lower neutral hydrogen fraction extremes in each redshift interval. Solid circles represent $x_{\rm HI}$ estimates by Fan et al. (2006); empty squares denote the results obtained in this work.

tral hydrogen. In this process, photons are removed from the line of sight (LOS) resulting in an attenuation of the source flux, the so-called Gunn-Peterson (GP) effect. For these reason QSO/GRB absorption spectra are recognized as very powerful tools for measuring the neutral hydrogen fraction $x_{\rm HI}$ in the InterGalactic Medium (IGM), and hence for determining $z_{\rm rei}$. Moreover, the observed Lyα Luminosity Function (LF) of LAEs can be used to infer the ionization state of the IGM at redshifts close to those of the star-forming galaxies and hence to reconstruct the reionization history. In this work, we compare the predictions of theoretical models of reionization with QSOs, GRBs, and LAEs observations.

2. Reionization models

We present a semi-analytical model of cosmic reionization, developed by Choudhury & Ferrara (2005) and Choudhury & Ferrara (2006) and further refined by Choudhury et al. (2008). This model, hereafter called CF05, allows to build a wide range of reionization scenarios which match many observational constraints (ranging from WMAP5 to SDSS data) and differ for $z_{\rm rei}$ and for the IGM properties at $z \geq 6$. In order to constrain reionization we have adopted the CF05 model to set up two different reionization scenarios, namely: (i) an early reionization model (ERM), favored by WMAP data, characterized by a highly ionized IGM at $z \approx 6$, and (ii) a late reionization model (LRM), in which $z_{\rm rei} \approx 6$, as suggested by the SDSS results. The $x_{\rm HI}$ predicted by the two models is shown in Fig.1. Moreover, we have developed a semi-analytical model to simulate QSO absorption spectra starting from the CF05 predictions (Gallerani et al. 2006).

3. Results

3.1. QSOs absorption spectra

We use observational data including 17 QSOs obtained by Fan et al. (2006). We divide the observed spectra into two redshift-selected sub-samples: the "Low-Redshift" (LR) sample ($5.7 < z_{\rm em} < 6$), and the "High-Redshift" (HR) one ($6 < z_{\rm em} < 6.4$). By comparing the the Largest Gap[1] Width (LGW) distribution[2] obtained from the observed spectra with simulations (Fig.2) we find that both the ERM and the LRM provide a good fit to observational data. We exploit this agreement to derive an estimate of $x_{\rm HI}$. We find $\log_{10} x_{\rm HI} = -4.4^{+0.84}_{-0.90}$ at $z \approx 5.3$, and $\log_{10} x_{\rm HI} = -4.2^{+0.84}_{-1.0}$ at $z \approx 5.6$. Although the predicted LGW distributions are quite similar for the two models considered, in the HR case we find that a neutral hydrogen fraction at $z \approx 6$ higher than that one predicted by the LRM would imply an even worst agreement with observations, since a more abundant HI would produce a lower (higher) fraction of LOS characterized by the largest gap smaller

[1] Gaps are defined as contiguous regions of the spectrum characterized by a transmitted flux lower than a flux treshold $F_{\rm th} = 0.1$.

[2] The LGW distribution quantifies the fraction of LOS which are characterized by the largest gap of a given width.

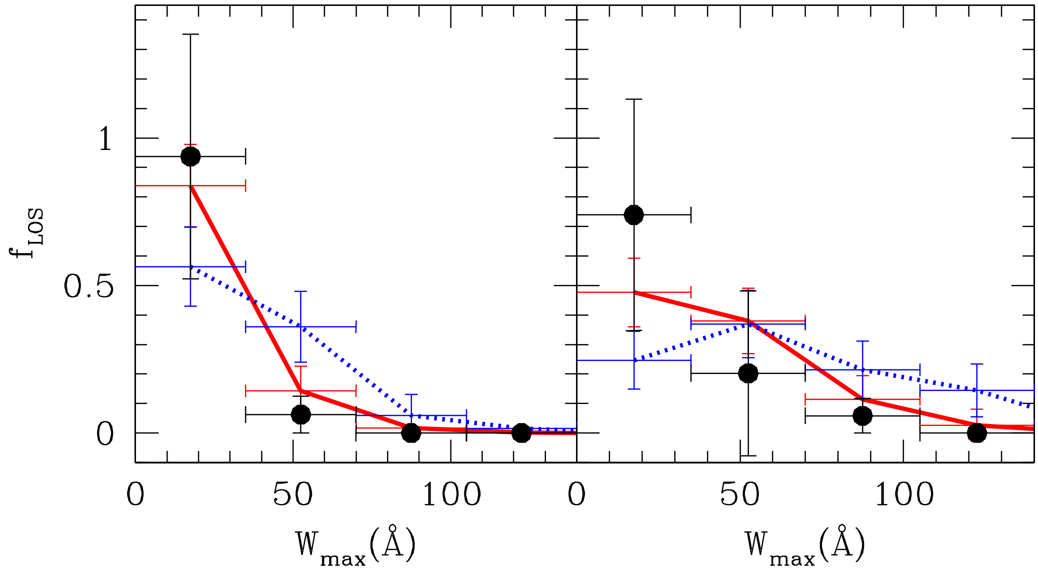

Fig. 2. LGW distribution for QSOs with $z_{em} < 6$ (left) and $z_{em} > 6$ (right). Filled circles represent observational data. Solid red (dotted blue) lines show the ERM (LRM) predictions. Vertical error bars measure poissonian noise, horizontal errors define the bin for the gap widths.

(higher) than 40 Å with respect to observations. Thus, this study suggests $x_{HI} < 0.36$ at $z = 6.32$ (Gallerani et al. 2008a).

3.2. GRBs absorption spectra

We have analyzed the optical afterglow spectrum of the GRB 0509004 at $z = 6.29$ by measuring the LGWs in its Lyα forest as a function of the flux threshold F_{th} used to define gaps. Starting from a large sample of synthetic spectra, we have computed the probability to find gaps of these widths in absorption spectra obtained through the ERM and LRM (Fig.3). We find that the ERM is two times more predictable than the LRM, thus confirming the results found in the case of QSOs, i.e. that a highly ionized Universe at $z \approx 6$ is favored by current observations (Gallerani et al. 2008b).

3.3. LAEs luminosity function

We have built up a semi-analytic model of LAEs to compute the evolution of the *Lyα* LF of star forming galaxies at redshifts approaching z_{rei}. We have fixed x_{HI} to the predictions of the ERM and LRM at $z = 5.7$ and $z = 6.6$ leaving only the star formation efficiency and the effective escape fraction of photons as free parameters. The results are shown in Fig.4. The ERM provides a good fit to observational data, implying that no sudden change in the ionization state of the IGM at $z \approx 6$ is required to explain the evolution of the *Lyα* LF (Dayal et al. 2008). The ERM has been also used by Dayal et al. (2009a) to predict the LAEs LF up to $z = 7.6$ and by Dayal et al. (2009b) to study the dust content of LAEs.

4. Conclusions

We have presented a semi-analytical model which allows to simulate QSOs, GRBs, and LAEs spectra. Synthetic spectra have been analyzed statistically and the theoretical predictions compared with observations. We have shown that current data do not require any sudden change in the IGM ionization level at $z \approx 6$, favouring a highly ionized IGM at these epochs. The overall result points towards an extended reionization process which starts at

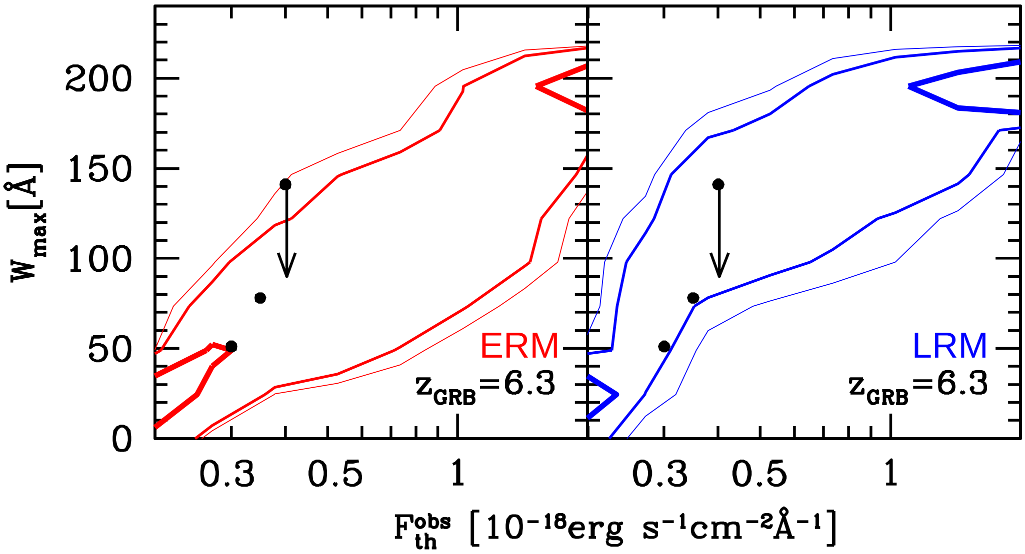

Fig. 3. Isocontours of the probability that the afterglow spectrum associated with a GRB at redshift z_{GRB} = 6.3, contains a largest gap of size in the range [W_{max}, $W_{max} + dW$], with dW = 20 Å, for a flux threshold F_{th}. The left (right) panel shows the results for the ERM (LRM). The isocontours correspond to probability of 5%, 10%, and 40%. The black points indicates the position in the (W_{max}, F_{th}^{obs}) plane of GRB 050904. The point with arrow means that the gap size should be considered as an upper limit, since the corresponding dark region could be affected by the presence of a DLA.

$z \gtrsim 11$ and completes at $z_{rei} \gtrsim 7$, in agreement with the recent WMAP5 data.

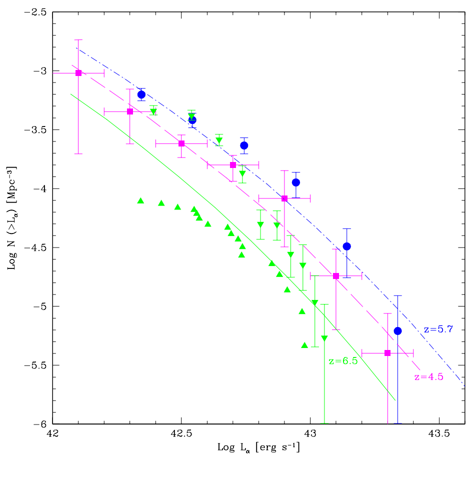

Fig. 4. LAE LF for the ERM at z = 5.7 (dot-dashed), z = 6.56 (solid). Points represent the data at z = 5.7 (circles; Shimasaku et al. (2006)), z = 6.56 (downward/upward triangles represent upper/lower limits; Kashikawa et al. (2006)).

References

Choudhury T. Roy et al., 2008, MNRAS, 385, L58

Choudhury T. Roy & Ferrara A., 2006, MNRAS, 371, L55

Choudhury T. Roy & Ferrara A., 2005, MNRAS, 361, 577

Dayal P. et al., 2009, arXiv:0907.4989

Dayal P. et al., 2009, arXiv:0907.0337

Dayal P. et al., 2008, MNRAS, 389, 1683

Dunkley J. et al. 2009, ApJS, 180, 306

Fan X. et al. 2006, AJ, 132, 117

Gallerani S. et al., 2008b, MNRAS, 388, L84

Gallerani S. et al., 2008a, MNRAS, 386, 359

Gallerani S. et al., 2006, MNRAS, 370, 1401

Greiner J. et al., 2009, ApJ, 693, 1610

Kashikawa N. et al, 2006, ApJ, 648, 7

Salvaterra R. et al, 2009, arXiv:0906.1578

Shimasaku K. et al., 2006, PASJ, 58, 313

Stark D. P. et al., 2007, ApJ, 663, 10

Tagliaferri G. et al., 2005, A&A, 443, L1