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LARGE SCALE OPACITY FLUCTUATIONS IN THE LYMAN ALPHA FOREST: DO QSOS DOMINATE THE UVB AT Z∼5.5-6?

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Abstract. The Lyman-alpha forest in the post-reionization Universe shows surprisingly large opacity fluctuations over large (50 cMpc/h) spatial scales at $5.4 \leq z \leq 5.8$. These fluctuations are modelled using a hybrid approach utilizing the large volume Millennium simulation to predict the spatial distribution of QSOs combined with smaller scale post-processed radiative transfer simulations that account for the galaxy contribution. Realictic absorption spectra that account for the contribution of galaxies and QSOs to the ionising UV background are then produced. This improved model confirm our earlier findings that a significant (≥50%) contribution of ionising photons from QSOs can explain the large reported opacity fluctuations on large scales. The inferred QSO luminosity function is thereby consistent with recent estimates of the space density of QSOs at those redshifts.

Keywords: Cosmology: theory - Methods: numerical - diffuse radiation - IGM: structure - Galaxy: evolution - quasars: general

1 Introduction

The Lyα forest is the primary probe of the ionisation state of hydrogen in the post-reionization Universe (see Becker et al. 2015a for a recent review). In a recent paper, Becker et al. (2015b) presented measurements of the Lyα opacity PDF averaged over scales of 50 cMpc/h in the redshift range $4 \leq z \leq 6$ based on a sample of QSO absorption spectra. They found large fluctuations of the mean flux at $z \geq 5.4$ and argued that the opacity fluctuations are due to fluctuations of the ionising UV background aided by fluctuations of the mean free path of ionising photons.

Our recent full post-processed radiative transfer simulations of the reionization of hydrogen by (faint) galaxies show only rather moderate fluctuations of the UV background and the mean free path in the post-overlap phase of reionization (Chardin et al. 2015). This led us to suggest that much rarer brighter sources like QSOs with space densities of $\sim 10^{-6}\,\mathrm{Mpc}^{-3}$ may contribute significantly to the ionising background at $z \sim 5.5 - 6$ and be responsible for the substantial opacity fluctuation at scales of 50 cMpc/h at this redshift. We investigate here in details the implications of this possible explanation by abundance matching the QSO luminosity function in a large volume and by looking at the contribution of QSOs to the ionising UV background at $z > 5$.

In Sect. 2 we present our hybrid approach utilising the large volume Millennium simulation to model the spatial distribution of QSOs combined with smaller scale full hydrodynamical simulations performed with RAMSES and post-processed with the radiative transfer code ATON. Sect. 3 presents our results with regard to spatial fluctuations of the photoionisation rate and the corresponding opacity fluctuations in the Lyα forest. We give our conclusions and outlook in Sect. 4.

2 Methodology

2.1 A combined UVB model for galaxies and AGNs

For the galaxy population, the simulation of the evolution of the dark matter and the hydrodynamics of the gas were performed with the RAMSES code (Teyssier 2002) on a coarse, fixed grid discretized in 512^3 cells with a

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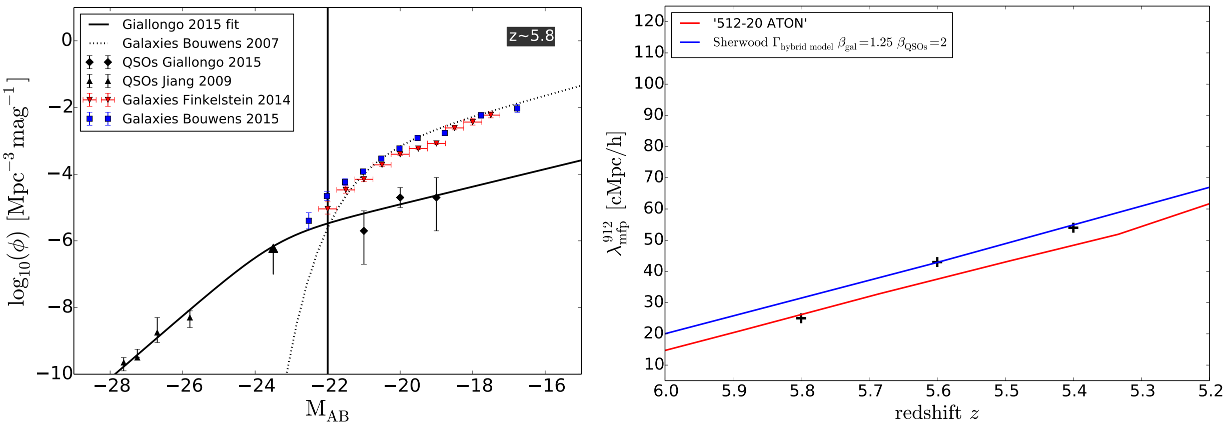

Fig. 1. Left: Fit to the QSO luminosity function (solid black) obtained by Giallongo et al. 2015 and a fit to the galaxy luminosity function (dotted balck) obtained by Bouwens et al. (2007). **Right:** The range of mean free path values assumed in our models. The solid red curve shows the evolution of the mean fee path as a function of redshift in our ATON 512-20 radiative transfer simulation. The different black crosses show the values assumed in our different models with fixed mean free path. The blue curve shows the evolution of the mean free path in the Sherwood simulation for different values of the mean photoionization rate in the three redshift bins, using the converged value of $<\Gamma>$ in our hybrid model.

box size of 20 cMpc/h. The radiative transfer calculations were performed in post-processing with the ATON code (Aubert & Teyssier 2008) with a monochromatic treatment that assumes all ionizing photons to have an energy of 20.27 eV. Ionising sources were placed in the dark matter haloes identified in the RAMSES simulation and assumed to emit continuously. The ionising luminosities were calibrated assuming a linear scaling of the ionising luminosity with the mass of dark matter haloes in order to reproduce a reionization history that matches Lyα forest data (see Chardin et al. 2015). The corresponding photoionisation rate due to the galaxy population in this small volume is then called $\Gamma_{\rm gal}^{\rm fiducial}$.

For the AGNs counterpart, we populate DM haloes in the Millennium simulation with sources drawn from a luminosity function guided by the observed space density of QSOs from Giallongo et al. (2015) at these redshifts (see left panel of Fig. 1). We sample the luminosity function from the brightest luminosity present in our 500^3 $({\rm Mpc/h})^3$ volume which corresponds to $M_{\rm AB} \sim -27$ and we adopt a lower limit of $M_{\rm AB} = -22$ for the faintest QSOs and assume that the other QSOs with a fainter luminosity are part of the galaxy population. We then compute the photoionization rate $\Gamma_{\rm QSO}^{\rm fiducial}$ due to these bright sources at every position in the volume assuming a mean free path for the ionising photons with the simple attenuation model used by Becker et al. (2015b).

We then combine the photoionisation rates due to AGNs in this large volume with the ionising UV background due to the much more numerous galaxies driving reionization in our smaller scale ATON simulation. We thereby combine the contributions from galaxies and QSOs as follows: $\Gamma_{\rm gal+QSO} = \Gamma_{\rm gal} + \Gamma_{\rm QSO} = \beta_{\rm gal}\Gamma_{\rm gal}^{\rm fiducial} + \beta_{\rm QSO}\Gamma_{\rm QSO}^{\rm fiducial}$. $\beta_{\rm gal}$ and $\beta_{\rm QSO}$ are the factors by which we need to rescale the luminosities of galaxies and QSOs in order to match the PDF of the Lyα effective optical depth.

In the redshift range we are interested in here, $z = 5.4 - 5.8$, the mean free path of ionising photons is still rather uncertain and we have first explored a range of fixed values as shown by the small crosses in the right panel of Figure 1. Assuming a fixed mean free path is obviously a rather poor approximation as the large UV fluctuations due to QSOs will also result in large fluctuations of the mean free path. Davies & Furlanetto (2016a) argued that the mean free path should depend as a simple power law on the photo-ionisation rate and density,

$$\lambda_{\rm mfp}(\Gamma) = \lambda_0(\Gamma/\Gamma_0)^{2/3}\Delta^{-\gamma}. \tag{2.1}$$

Here Δ is the overdensity in the simulation cells and γ sets the power law dependance on the overdensity for the mean free path. Davies & Furlanetto (2016b) choose a value of $\gamma = 1$ and we will investigate this model here as well. For the normalisation of the mean free path in equation 2.1 we have chosen λ_0 and Γ_0 such that we reproduce the mean free path in the Sherwood simulation (see Bolton et al. 2017) in the limit of a spatially constant UV background. This results in the evolution of the average mean free path shown in the right panel

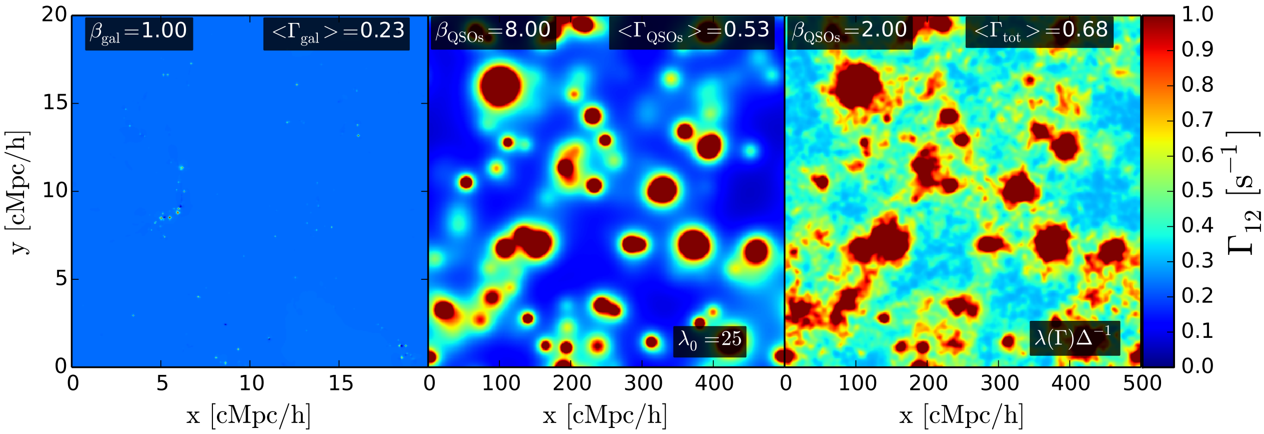

Fig. 2. Left: Spacial distribution of the photoionization rate $\Gamma_{\rm gal}$ in a slice of our 20 Mpc/h radiative transfer simulation at redshift $z \sim 5.8$ (galaxies only). **Middle:** Spatial distribution of the photoionization rate ($\Gamma_{\rm QSO}$) due to QSOs through the Millenium simulation at redshift $z \sim 5.8$ for a constant mean free path of $\lambda_0 = 25$ cMpc/h. **Right:** Spatial distribution of the photoionization rate due to QSOs plus galaxies ($\Gamma_{\rm tot} = \Gamma_{\rm QSO} + \Gamma_{\rm gal}$) for a Γ dependant parametrization of the mean free path $\lambda(\Gamma)$ according to equation 2.1 with $\lambda_{\rm mfp} \propto \Delta^{-1}$ and $\beta_{\rm gal} = 1.25$.

of Figure 1 as the blue line.

3 Results

Figure 2 shows maps of the photoionisation rate $\Gamma_{\rm gal}$ and $\Gamma_{\rm QSO}$ at $z \sim 5.8$ assuming a fixed mean free path. The maps shown are the ones that best match the observed cumulative Lyα effective optical depth PDF as shown in Figure 3. For the fit to the QSO luminosity function as in Giallongo et al. (2015) the luminosities need to be rescaled by a factor $\beta_{\rm QSO} = 8$ in order to match the observed Lyα effective optical depth PDF at redshift z=5.8 for our models with mean free path of 25 cMpc/h. These rather high values of $\beta_{\rm QSO}$ are due to the fact that our assumed mean free path is lower than the (mean) distance between the QSOs in our model. As already discussed neglecting the effect of the QSOs on the mean free path is a bad approximation.

In figure 3, we compare the Lyα effective optical depth PDF for the case of a constant mean free path and with a Γ dependant mean free path parametrization as described in section 2.1. The value of $\beta_{\rm QSOs}$ decreases to 2 with the Γ dependant mean free path parametrization at z=5.8 if we assume the mean free path to depend on overdensity as Δ^{-1}. Large values of the mean free path close to ionized regions have the effect of increasing the $\langle\Gamma_{\rm QSOs}\rangle$ values. Therefore, for a given luminosity function, adopting a photoionisation dependant mean free path parametrization in the combined UVB model leads to a lower value of $\beta_{\rm QSOs}$ required to generate photoionization rate fluctuations that match the PDF of $\tau_{\rm eff}$. Thus, the recent determination of the AGN luminosity function by Giallongo et al. (2015) only need to be moderately rescaled to be consistent with the Lyα forest PDF data.

4 Conclusions

We have combined here high-resolution full radiative transfer simulations with the large volume Millennium simulation to model large scale opacity fluctuations due to a significant contribution of QSOs to the UV background at $z \geq 5$.

We can reproduce the reported broad distribution of the Lyα opacity on scales ≥ 50 cMpc/h with a contribution $\geq$50% of QSOs to the ionising emissivity. The ionising emissivity of QSO required to reproduce the observed opacity depends rather sensitively on the assumed mean free path and its dependence on the local ionising UV flux and over-density. For assumptions for the mean free path and its dependence suggested by our simulations the required ionising emissivity is similar to that predicted by the recent determination of the QSO luminosity function at this redshift by Giallongo et al. (2015).

The model predicts a strong correlation of low Lyα opacity with the presence of QSOs close to the line-of-sight. This differs strongly from the predictions of alternative models that predict a strong correlation

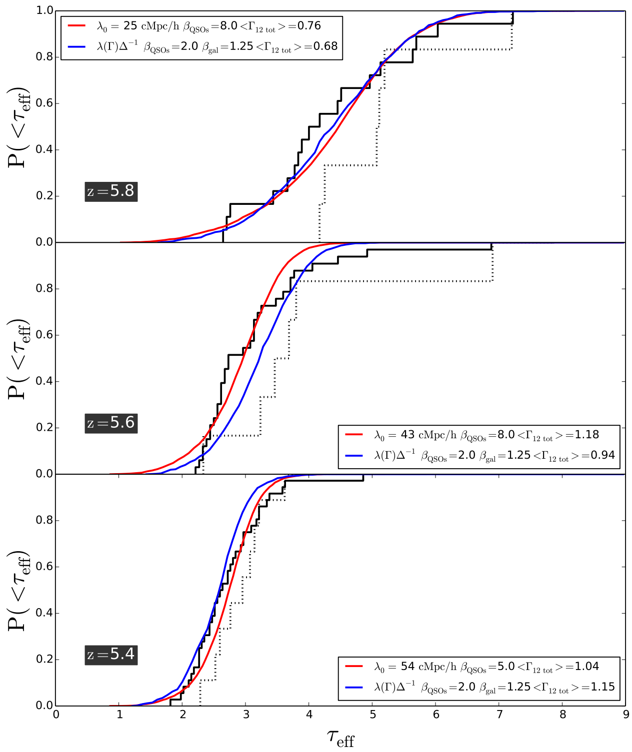

Fig. 3. PDF of $\tau_{\rm eff}$ for models with the (rescaled) luminosity funtion of Giallongo et al. 2015 at the three redshifts with values $\beta_{\rm gal}$ and $\beta_{\rm QSOs}$ as indicated in the plots. The red curves shows the case with a constant mean free path $\lambda_{\rm mfp} = \lambda_0$ (with $\beta_{\rm gal} = 1$) while the blue curve show case with a varying mean free path adopting the parametrization chosen in equation 2.1. The black solid step function shows the data from Becker et al. (2015b) based on their own sample of QSO spectra combined with the sample of Fan et al. (2006) while the dotted black step function is for the Becker et al. (2015b) sample only.

or anti-correlation of Lyα opacity with over-density on large scales (see D'Aloisio et al. 2015 and Davies & Furlanetto 2016a). The strength of the correlation should depend on the duty cycle as well as the the possible beaming of the QSOs.

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