Peering towards Cosmic Dawn
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Quasars at the Cosmic Dawn: effects on Reionization properties in cosmological simulations

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Abstract. We study a model of cosmic reionization where quasars (QSOs) are the dominant source of ionizing photons at all relevant epochs. We employ a suite of adaptive hydrodynamical simulations post-processed with a multi-wavelength Monte Carlo radiative-transfer code and calibrate them in order to accurately reproduce the observed quasar luminosity function and emissivity evolution. Our results show that the QSO-only model fails in reproducing key observables linked to the Helium reionization, as the temperature evolution of the inter-galactic medium (IGM) and the HeII effective optical depth in synthetic Lyα spectra. Nevertheless, we find hints that an increased quasar contribution can explain recent measurements of a large inhomogeneity in the IGM at redshift $z \approx 5$. Finally, we devise a method capable of constraining the QSOs contribution to the reionization from the properties of the HeII Lyα forest at $z \approx 3.5$.

Keywords. cosmology: theory, early universe, intergalactic medium, quasars: general, methods: numerical, hydrodynamics, radiative transfer

1. Introduction

The Epoch of Reionization (EoR) represents the last global phase-change in the universe, when the inter-galactic medium (IGM) transformed from neutral to highly-ionized, but very little is known about it. In the standard model of reionization, inter-galactic Hydrogen is ionized by high-redshift star-forming galaxies at redshift $z \gtrsim 6$, while the Helium reionization (HeII $\rightarrow$ HeIII) is accomplished by quasars (QSOs) at redshift $z \approx 2.7$–3 (McQuinn 2016). This picture is supported by a number of observational evidence, as e.g. the evolution of the Hydrogen ionized fraction, of the IGM temperature and of the effective optical depth of the HI and HeII Lyα forests, as well as from integral constraints coming from the cosmic microwave background (Fan *et al.* 2006).

In a recent observational campaign, Giallongo *et al.* (2015) identified a large number of candidate faint quasars (but see Parsa *et al.* 2017), thanks to the inclusion of X-ray observations in the selection pipeline, and constrained the faint end of the QSOs luminosity function (LF) at redshift $4 \leqslant z \leqslant 6$. Employing these new observations Madau & Haardt (2015, MH15 hereafter) showed that QSOs alone supply enough ionizing photons to power both the Hydrogen and the Helium reionization. Following this works,

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the QSO-only reionization model has been investigated employing different techniques (see e.g. Hassan *et al.* 2017, Kulkarni *et al.* 2017, Chardin *et al.* 2017, Mitra *et al.* 2017). However, different studies reached different conclusions regarding the relative importance of QSOs and galaxies during the EoR. To amend this, we present here a new set of numerical simulations that faithfully incorporate the QSO LF by Giallongo *et al.* (2015) and implements the QSO-only reionization model. They are devised to produce reliable synthetic observations of global IGM properties and, in particular, of the Lyα forest in order to enable a thorough comparison to a large set of observational constraints.

2. Simulations

We make use of four hydrodynamical simulations performed using the RAMSES code (Teyssier 2002), each following the evolution of a box of comoving side $L = 100\,h^{-1}$ Mpc from $z_{\rm init} = 99$ to $z_{\rm fin} \approx 3.5$. We employ the Planck Collaboration *et al.* (2015) cosmology and assume the gas has primordial composition and follows an ideal equation of state with adiabatic index $\gamma = 5/3$. Each simulation is post-processed with the RADAMESH code, that solves the radiative-transfer equations using a multi-wavelength spatially- and time-adaptive ray-tracing Monte Carlo technique in the photon energy range $[1, 40]$ ryd.

Quasars are placed at the center of dark matter (DM) haloes and their luminosity is related to the halo mass via an abundance matching approach (Silk & Rees 1998, Wyithe & Loeb 2002) calibrated using the observed QSO LF. Quasars are assumed to have a lightbulb emission profile with a lifetime of 45 Myr. We extract synthetic spectra at each redshift along random sightlines including thermal and Doppler broadening.

We validate our simulation suite by comparing: (i) the evolution of the Hydrogen and Helium ionized fraction with a compilation of observations summarized in Bouwens *et al.* 2015; (ii) the cosmic microwave background optical depth measurements of the Planck Collaboration *et al.* 2016 with the value inferred from our simulation suite. Overall, our simulations are in good agreement with observational constraints. Similarly, they are consistent with the MH15 analytical model, although the realistic positions of sources in our numerical study produces a slower reionization at high redshift that becomes faster than in MH15 towards its end. The net effect is that in our simulations the end of Helium reionization is almost coincident with the Hydrogen one.

3. Results

The temperature at mean density (T_0) is widely-used to characterize the IGM. We show its evolution with redshift in Fig. 1. Since the ending phases of HI and HeII reionization almost coincide, their heat injection in the IGM produces a single maximum in $T_0(z)$, in contrast with the prediction from the standard model of reionization. Available data show a peak in the IGM temperature at redshift $z \approx 3.5$, usually interpreted as a signature of HeII reionization. In the QSO-only model, there is no physical mechanism able to inject enough heat into the IGM at such redshift, and therefore the predicted T_0 (dashed line in the Figure) falls short of the observed values (symbols). Consistent results are obtained comparing the predicted evolution of the HeII Lyα forest effective optical depth with values measured from QSO sightlines.

Moving beyond average quantities, the IGM shows a degree of inhomogeneity at redshift $5 \lesssim z \lesssim 6$ that is difficult to reconcile with the outcomes of simulations (Becker *et al.* 2015, Chardin *et al.* 2017, but see Gnedin *et al.* 2017). In Fig. 2 we show the cumulative distribution of effective optical depths in skewers of length $50\,h^{-1}$ Mpc extracted from synthetic HI Lyα spectra (solid lines, the shading encloses the central 68% of the

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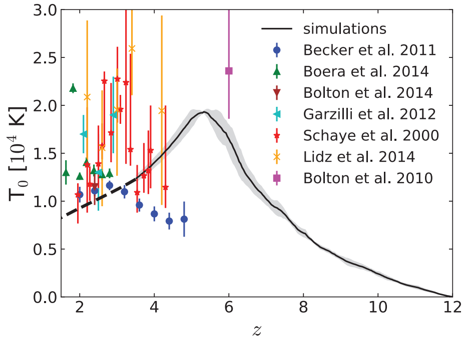

Figure 1. Redshift evolution of the IGM temperature at mean density. Shown are: the simulated evolution (solid line), its scatter (shading enclosing the central 68% of the data), its predicted evolution at low redshift (dashed line) and a collection of observations (symbols).

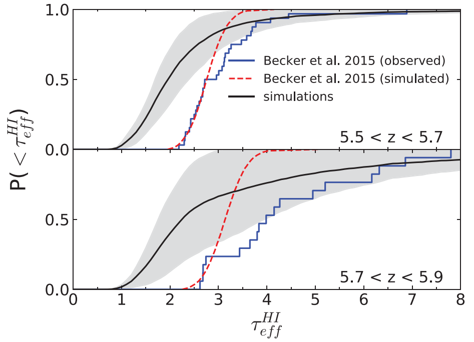

Figure 2. Cumulative distribution of effective optical depths in skewers extracted from our simulations (solid line, the shading encloses the central 68% of the data), compared to observations (histogram) and predictions using a standard reionization history (dashed line) from Becker *et al.* (2015).

data) for the two highest-redshift bins probed by observations (histograms). The dashed lines indicate the prediction of numerical simulations employing a standard reionization history and calibrated to match the low-$\tau_{\rm eff}$ data (Becker *et al.* 2015). The standard reionization history is unable to reproduce the large inhomogeneity observed at $5.5 \lesssim z \lesssim 6$, while this is a natural outcome of the QSO-only model (that was not calibrated against this kind of observations). The large luminosity of QSOs produces regions where $\tau_{\rm eff}$ is much lower than observed. It is therefore tempting to interpret this result as a hint that a sizable contribution from QSOs, combined with star-forming galaxies dominating the ionizing photons budget at $z \gtrsim 4$, could help reproducing the observed distribution of optical depths. These result confirms earlier findings of Chardin *et al.* (2017), where a DM-only density field was combined with a (much smaller) radiative-transfer simulation to estimate the effect of a varying QSOs abundance. However, the effect of different sources on the IGM is highly non-linear and therefore accurate simulations of this 'hybrid' reionization history are needed in order to make sensible claims.

In order to facilitate future numerical efforts of this kind, it would be optimal to have an estimation of the relative importance of QSOs and galaxies at $z \gtrsim 4$. With this in mind, we exploit the detailed synthetic spectra extracted from our simulations in order to devise an observational test able to constrain such quantity. We perform a careful investigation of different statistical ways to characterize the Lyα forest of both HI and HeII. We identify the most-promising measure of the QSOs contribution to the EoR in the fraction of pixels of the HeII Lyα forest spectra found within a 'flux window' (FTW) and 'dark gap' (DG) as defined in Compostella *et al.* (2013). In Fig. 3 we show the different evolution with redshift of these quantities for the QSO-only model (dots) and in a standard reionization history (squares, taken from Compostella *et al.* 2013), that clearly differs in the two models investigated. Concerning the DG, the largest difference is found at $z = 5$, but the limited availability of QSO sightlines probing the HeII Lyα forest prevents an investigation at such large redshift. More promisingly, at $z = 3.5$ (the lowest probed by our simulation suite) the difference between the predicted fraction $f_{\rm FTW}$ in the two reionization scenarios is the largest, opening up the interesting possibility to employ the available observations to place constraints on the QSOs contribution to the

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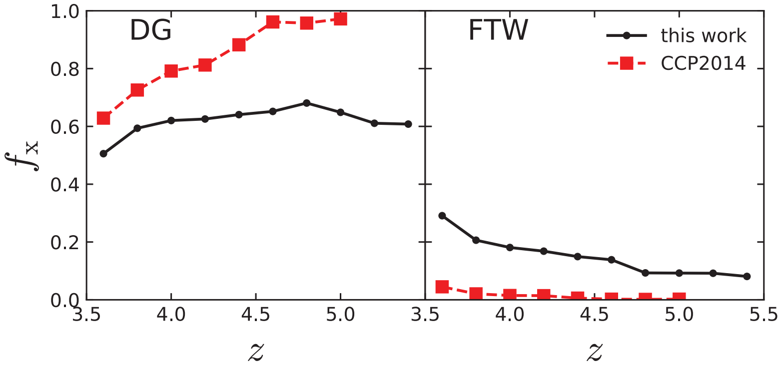

Figure 3. Fraction of pixel in the HeII Lyα forest associated with a 'dark gap' (DG, left) of 'flux transmission window' (FTW, right) as a function of redshift for the QSO-only reionization model (dots) and a standard reionization history (squares).

Hydrogen EoR. Moreover, extrapolating these trends suggests an even-larger difference at $z \gtrsim 3$. We plan to apply this method on real QSO spectra in future works.

4. Conclusions

We employ a suite of hydrodynamical simulations post-processed with a multi-wavelength multi-species adaptive radiative-transfer code in order to accurately simulate a reionization history entirely dominated by QSOs at all epochs. We compare synthetic observations of global and local properties of the IGM to available data and conclude that the scenario investigated is unable to match observables linked to the HeII reionization (as e.g. the IGM temperature and HeII optical depth evolution). Nevertheless, we find hints that a sizable contribution from QSOs at $z \gtrsim 4$ can alleviate the tension with observations of IGM inhomogeneity at $5 \lesssim z \lesssim 6$. Finally, we exploit the detailed modeling of the IGM to produce synthetic Lyα forest spectra and identify in the fraction of pixels classified as 'dark gap' or 'flux transmission window' the most promising observational proxy for the contribution of QSOs to the ionizing photons budget at high redshift.

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