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Probing inhomogeneity in the helium ionizing UV background

Sean Morrison¹,^{*} Matthew M. Pieri,¹ David Syphers² and Tae-Sun Kim³

¹*Aix Marseille Univ, CNRS, CNES, LAM, Marseille, France, 13388*

²*Eastern Washington University, Department of Physics, Cheney, WA 99004, USA*

³*University of Wisconsin Madison, Department of Astronomy, Madison, WI 53706, USA*

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ABSTRACT

We present an analysis combining the simultaneous measurement of intergalactic absorption by hydrogen (H I), helium (He II), and oxygen (O VI) in UV and optical quasar spectra. The combination of the H I and He II Lyman-alpha forests through η (the ratio of column densities of singly ionized helium to neutral hydrogen) is thought to be sensitive to large-scale inhomogeneities in the extragalactic UV background. We test this assertion by measuring associated five-times-ionized oxygen (O VI) absorption, which is also sensitive to the UV background. We apply the pixel optical depth technique to O VI absorption in high and low η samples filtered on various scales. This filtering scale is intended to represent the scale of any coherent oxygen excess/deficit. We find a 2σ detection of an O VI opacity excess in the low η sample on scales of ~ 10 cMpc for HE 2347-4342 at $\bar{z} \approx 2.6$, consistent with a large-scale excess in hard UV photons. However, for HS 1700 + 6416 at $\bar{z} \approx 2.5$ we find that the measured O VI absorption is not sensitive to differences in η . HS 1700 + 6416 also shows a relative absence of O VI overall, which is 6σ inconsistent with that of HE 2347-4342. This implies UV background inhomogeneities on $\gtrsim 200$ cMpc scales, hard UV regions having internal ionization structure on ~ 10 cMpc scales, and soft UV regions showing no such structure. Furthermore, we perform the pixel optical depth search for oxygen on the He II Gunn-Peterson trough of HE 2347-4342 and find results consistent with post-He II-reionization conditions.

Key words: intergalactic medium – quasars: absorption lines – diffuse radiation.

1 INTRODUCTION

After the formation of the cosmic microwave background, the Universe recombined to produce a homogeneous, neutral, and diffuse medium. Between $6 < z < 30$ the Universe transitioned from a predominately neutral to a predominately ionized state (Fan et al. 2006). In the period leading to the end of reionization, enough neutral hydrogen (H I) remained to generate a Gunn–Peterson (GP) trough in quasar absorption, whereby blanket absorption is seen bluewards of the quasar Lyman α ($\lambda 1216$; Ly α) emission line. At lower redshifts this blanket is lifted and a H I Ly α forest is observed reflecting the residual neutral gas. Helium is singly ionized during this period, which (given its status as a hydrogen-like ion) gives rise to the helium-II Ly α ($\lambda 304$) absorption.

Following the epoch of hydrogen reionization, quasars and other ionizing sources proceeded to further ionize singly ionized helium (He II) in a stage known as helium-II reionization. Shull et al. (2010) claim that this epoch ended around $z_r \sim 2.7$, though other estimates claim it ended as early as $z_r \sim 3.2$ (Syphers et al. 2011; Worseck et al. 2016). This is a subject of ongoing study.

Various source populations contribute to the reionization of the Universe and keep it ionized until the present day. The dominant sources of ionizing UV photons are thought to be active galactic nuclei associated with quasars and star-forming galaxies. Quasars contribute proportionately more hard UV photons and so their growing contribution leads to the epoch of He II reionization (Furlanetto & Oh 2008). Regions of excess ionizing photons around individual sources are known as ‘proximity zones’. The extent of the excess depend on factors such as the photon escape fraction of the surrounding gas, as well as the amount of time that the source has been active.

Fluctuations in the UV background may give rise to spatial variation in H I and He II. However, when the mean free path of ionizing photons is larger than the mean separation of closest sources, such effects are suppressed and potentially insignificant. At $z \sim 2$ – 3 the mean free path of H I ionizing photons is ~ 100 – $300 h^{-1}$ comoving megaparsec (cMpc) (Croft 2004; Rudie et al. 2013), which is larger than the mean separation of the sources. The mean free path of harder He II ionizing photons is significantly shorter in this redshift range. Various factors play a role in its determination (e.g. Faucher-Giguère et al. 2009; Furlanetto 2009; Davies & Furlanetto 2014; Davies, Furlanetto & Dixon 2017) leading to scales of 20–100 cMpc at $2.5 < z < 3.2$. Most notably,

* E-mail: sean.morrison@lam.fr (SM); matthew.pieri@lam.fr (MMP)

Table 1. Ionization energies for a sample of atomic species (Kramida et al. 2018).

Element	Ionization energy (ev)							
	I	II	III	IV	V	VI	VII	VIII
H	13.59843449	...	...	...	...	...	...	...
He	24.58738880	54.4177650	...	...	...	...	...	...
O	13.618055	35.12112	54.93554	77.41350	113.8990	138.1189	739.32682	871.40988

the mean free path itself is thought to vary spatially (Davies et al. 2017) contributing to UV background fluctuations on scales of up to ~ 200 cMpc.

In the fluctuating Gunn–Peterson approximation (FGPA), H I Ly α opacity traces gas overdensities (Croft et al. 1998; Weinberg, Katz & Hernquist 1998). One justifying factor for this approximation is the large mean free path of H I ionizing photons above. Using the FGPA, H I opacity $\tau_{\text{H I}}$ can be used as an approximation of the intergalactic medium (IGM) density, while He II opacity $\tau_{\text{He II}}$ probes both the UV background and the IGM density. We can therefore combine these two quantities into a largely density independent ratio

$$\eta \equiv \frac{N_{\text{He II}}}{N_{\text{H I}}} \approx 4 \frac{\tau_{\text{He II}}}{\tau_{\text{H I}}} \quad (1)$$

to act as the standard observable for the hardness of the UV ionizing background. The factor of four arises from the ratio of wavelengths (ionization energies) between He and H. The approximation holds if line profiles are dominated by turbulent broadening over thermal broadening (since turbulent broadening affects species equally while thermal broadening does not). Large η equates to a soft radiation field, while small η equates to a hard radiation field.

The ratio η is sensitive to various physical effects. Graziani, Maselli & Maio (2019) used radiative transfer simulations to show that η is sensitive to IGM opacities on Mpc scales. On the other hand, η is also affected by systematic effects not directly related to ionization, the most dominant being the different thermal line broadening between the H I and He II (Fechner & Reimers 2007; McQuinn & Worseck 2014). Various studies have examined the use of η as a probe of the UV background fluctuations. McQuinn & Worseck (2014) argued that η shows no large fluctuations, and that fluctuations found in early studies were the result of continuum errors and low signal-to-noise. However, Syphers & Shull (2014) found η sensitivity to UV background fluctuations (using higher signal-to-noise data compared to early studies and more refined continuum estimates).

Since the main observables are quasars themselves, the proximity effect is often split into line-of-sight (where the source is the observed quasar) and transverse (where the line-of-sight passes through the sphere of influence of another quasar). Given that quasar luminosity is variable, fossil proximity zones around inactive quasars must also be considered (Oppenheimer & Schaye 2013; Oppenheimer et al. 2018). Segers et al. (2017) found that these proximity zones could maintain elevated densities of high ions for time-scales much greater than active galactic nuclei (AGNs) lifetimes.

In addition to utilizing H I and He II in the form of η , additional information can be obtained from the ratios of optical depths for various ionization species (Songaila, Hu & Cowie 1995; Bolton & Viel 2011). Since different species ionize when absorbing photons of different energies (Table 1), it is therefore possible to examine the abundance of various species to determine the spectral shape and intensity of the ionizing UV background (Agafonova et al. 2007).

Furthermore, we may use the spectral shape of the UV background, its intensity and the size, shape, and location of any inhomogeneities to study the ionizing sources. Attempts have been made to probe the UV background shape and He II reionization with C IV and Si IV observationally (Songaila et al. 1995) and using toy models (Bolton & Viel 2011). On the other hand, five-times ionized oxygen (O VI; $\lambda\lambda 1032, 1038$) is potentially useful as a tracer of hard UV conditions, and so can probe to the nature of the UV background when combined with η .

In this paper we present a new analysis combining measurements of η with intergalactic oxygen absorption in spectra of quasars HE 2347-4342 and HS 1700 + 6416. We combined the forward modelling approach for calculating η with the pixel optical depth method for measuring O VI (Cowie & Songaila 1998). We treat η as a good proxy for UV hardness and cut the O VI sample based on this proxy, with a simple high/low η split. We explore the filtering of η to study various physical scales and take novel approaches to analysing differences in O VI pixel optical depth samples. We compare the overall difference in O VI seen between our pair of quasar spectra to study line-of-sight scales. We further compare oxygen absorption in the He II GP trough to the He II forest in order to search for strong evolution associated with He II reionization.

We study large-scale inhomogeneities in the UV background both within lines-of-sight and between lines-of-sight. By using η as a proxy for excess hard UV photons rather than the location of observed quasars, we are able to include the contribution of fossil quasar proximity effects (assuming similar recombination times for He II and O VI). Despite our small analysis sample we are able to study inhomogeneous hardening of the UV background at and after He II reionization.

This paper is structured as follows: Section 2 describes the data and data reduction techniques. Section 3 outlines the forward modelling used to determine η . Section 4 gives a brief overview of the pixel optical depth method (POD) and then details our use of it in combination with high-low splits in η . Section 5 shows our results calculating differential oxygen opacity for various pixel sample splits. First we show the separation into high-low splits in η filtered on various physical scales, then the difference between lines-of-sight, and finally splitting the sample between GP trough and He II forest data. Section 6 discusses our results, tying together our various measurements to develop a coherent picture of UV background fluctuations, followed by conclusions in Section 7. Note that, unless otherwise stated, hereafter ‘Ly α ’ will refer only to the transition due to neutral hydrogen.

2 DATA

In order to study $2 < z < 3$ UV background inhomogeneity, we require both observer-frame UV and optical spectra. The UV spectral range gives us access to the He II Ly α forest, while the optical spectral range gives us the corresponding H I Ly α forest, and the O VI forest. We must limit ourselves to quasars that fulfil a number of requirements,

Table 2. Observations utilized.

QSO	z_{em}	Instrument	Exposures (s)	Resolution	Notes
HE 2347-4342	2.887	COS G140L/1230	1 × 11558	1500-4000	GTO 11528 (PI J. Green)
		COS G130M/1222	2 × 14814	16000-21000	GO 13301 (PI J. Shull)
		<i>VLT</i> -UVES	21600 + 28800	45000	Kim et al. 2013
HS 1700 + 6416	2.748	COS G140L/1230	1 × 15705	1500-4000	Syphers & Shull 2013
		COS G130M/1222	3 × 15694 + 1 × 12469	16000-21000	GO 13301 (PI J. Shull)
		<i>Keck</i> -HIRES	2 × 2800 + 1 × 3000	48000	C13H (PI W. Sargent) ¹

Note: ¹Retrieved from the KODIAQ database (Lehner et al. 2014; O’Meara et al. 2015, 2017)

Table 3. The signal-to-noise and redshift ranges of the paths utilized.

QSO	z_{em}	O VI	η (full path)	η (O VI)	GP
HE 2347-4342	2.887	z	$2.508 < z < 2.7$	$2.4 < z < 2.85$	$2.508 < z < 2.7$
		$\langle \text{S/N/resol} \rangle$	82	7.8 (He II), 173 (H I)	8.3 (He II), 162 (H I)	$2.7 \lesssim z \lesssim 2.85^1$ 153 (O VI), 240 (H I)
HS 1700 + 6416	2.748	z	$2.295 < z < 2.66$	$2.16 < z < 2.7$	$2.295 < z < 2.66$
		$\langle \text{S/N/resol} \rangle$	128	4.2 (He II), 154 (H I)	3.8 (He II), 147 (H I)

Note: ¹As described in Section 2.

(i) the optical spectra must be observed in high signal-to-noise ($\text{S/N} \gtrsim 100$ per resolution element; $\text{S/N} \gtrsim 50$ per pixel) and high spectral resolution ($R \gtrsim 50000$),

(ii) sufficient quasar continuum emission must remain for He II Ly α forest absorption analysis such as the signal-to-noise per resolution element is greater than 1.4 (signal-to-noise per pixel is greater than 0.5) i.e. the quasar must be a ‘He II quasar’,

(iii) a significant path in the He II Ly α forest must be available that does not show a GP trough.

There are only a small number of known He II quasars due to the cumulative impact of H I Lyman limit systems eroding the continuum emission. Of these only HE 2347-4342 ($z_{\text{em}} = 2.887$) and HS 1700 + 6416 ($z_{\text{em}} = 2.748$) fulfil our requirements (Tables 2 and 3). Redshift estimates for HE 2347-4342 vary from 2.885 (Fechner, Baade & Reimers 2004) to 2.905 (Shull et al. 2010). In both spectra, we discard the reddest $\sim 3000 \text{ km s}^{-1}$ in order to avoid intrinsic quasar effects. Our sample exceeds our minimum quality requirements in that the minimum S/N per resolution element is 2.39.

In addition to providing He II forest absorption at $z \lesssim 2.7$, HE 2347-4342 includes a GP trough that covers the redshift range, $2.7 \lesssim z \lesssim 2.85$ (with some transmission windows). We defined the GP trough in chunks of size $dz = 10^{-3}$ and designated them part of the trough when more than half the pixels have $\tau_{\text{He II}} > 5$ (following the method of Syphers et al. 2011). If the lowest quasar redshift estimate in the literature had been taken for HE 2347-4342, only ~ 3 per cent of the GP trough would have entered the proximity zone, thus the choice is of negligible importance.

2.1 HST COS data

The UV spectra were taken by *HST* COS (Table 2). The G140L/1230 spectrum for HS 1700 + 6416 is the same as analysed in Syphers & Shull (2013). For the G130M and remaining G140L/1230 (for HE 2347-4342) the extractions followed the same procedures outlined in Syphers & Shull (2013), with the precise details noted below.

While G130M data, as well as newer G140L data exists for HE 2347-4342 and HS 1700 + 6416, they do not provide the necessary path-length. Moreover the higher spectral resolution of G130M has

no impact since we filter to cMpc scales. *FUSE* spectra for HE 2347-4342 and HS 1700 + 6416 are available with comparable S/N per resolution element, however, they exhibit systematic errors in the zero-point flux (Zheng et al. 2004; Fechner et al. 2006). Therefore, we utilize exclusively COS G140L/1230 in the UV (aside from the exception discussed below).

In order to continuum normalize the UV spectra, we first identified regions relatively free of absorption and then used an iterative sigma clipping (Syphers & Shull 2013, 2014) until convergence is met. For both lines-of-sight, we extrapolate the continuum from the redward of the He II Ly α emission line to bluewards using a power-law fit ($\alpha_{\nu} = -0.4609$ for HE 2347-4342; $\alpha_{\nu} = -0.1348$ for HS 1700 + 6416), verifying that it matches high-transmission regions bluewards of any He II GP troughs. The resulting continuum normalized spectral regions utilized in our analysis are shown in Fig. 1.

G140L/1230 has significant wavelength calibration errors in the portion of data of interest here (Syphers & Shull 2013) due to a lack of usable lines in the onboard Pt/Ne lamp. Syphers & Shull (2013) found that improved calibration was possible by performing a cross-comparison with *FUSE* data aligning features in the G140L/1230 data with the more reliable wavelength calibration of *FUSE*. In this work, we use the reliable wavelength solution of G130M data to correct for any remaining calibration errors in both spectra.

2.2 Optical ground-based observations

The optical spectrum (Table 2) of HE 2347-4342 is the spectrum presented by Kim et al. (2013), taken with the *VLT* UVES at the resolution of 6.7 km s^{-1} and the $\text{S/N} \gtrsim 50$ per pixel in the Ly α forest and O VI region. We acknowledge that there has been some disagreement on the placement of the continuum (McQuinn & Worseck 2014), but as our analysis is driven by variation in η rather than the overall values, we are broadly resistant to this potential systematic error.

The optical spectrum of the quasar HS 1700 + 6416 (Table 2) comes from the *Keck* program C13H (PI W. Sargent). The extracted, continuum-normalized, and combined HIRES spectrum was downloaded from the Keck Observatory Database of Ionized Absorbers toward Quasars (KODIAQ) database (Lehner et al. 2014; O’Meara et al. 2015, 2017).

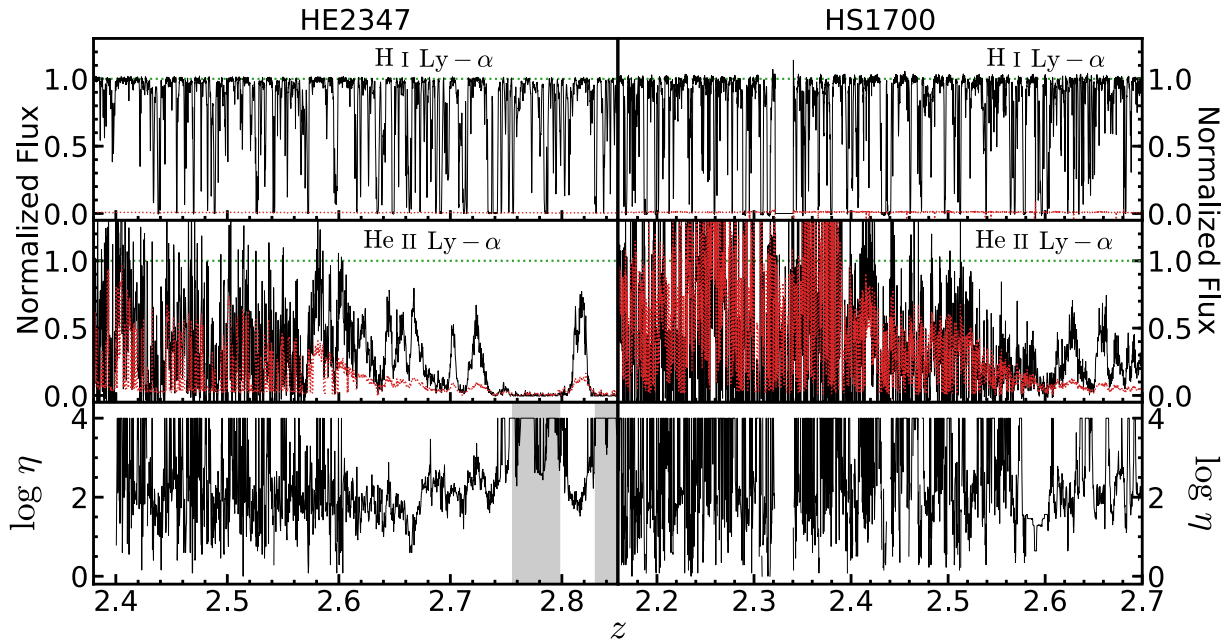


Figure 1. The continuum normalized spectra of HE 2347-4342 (left-hand panel) and HS 1700 + 6416 (right-hand panel) for H I Ly α (Top) and He II Ly α (Middle), with the flux shown in black, and the 1σ errors shown as the red dotted lines (online version only). The redshift range shown corresponds to the range utilized in our analysis. The bottom row shows the $\log \eta$ values in black for the full calculated range, with the grey bands denoting the region in the He II GP trough.

3 η FORWARD MODELLING

Early work calculating η through a direct ratio of opacities was not suited to the resolution and S/N of the available data (McQuinn & Worseck 2014; Syphers & Shull 2014). Others tried to measure η as a direct ratio of column densities (Kriss et al. 2001; Zheng et al. 2004; Fechner & Reimers 2007; Muzahid, Sriand & Petitjean 2011), but this is limited by degeneracies in line decomposition (Fechner & Reimers 2007). The modern approach of forward modelling was developed to mitigate these concerns (McQuinn & Worseck 2014; Syphers & Shull 2014).

We utilized this method and forward modelled the He II transmission from the H I transmission via a grid of η values (Heap et al. 2000; Fechner & Reimers 2007; McQuinn & Worseck 2014; Syphers & Shull 2014). As our spectrum contained no obvious emission lines within the range of interest, we censored any pixels with high normalized flux (flux > 1) to the normalized value of 1, removing the effect of these noisy pixels from the forward modelling.

This forward modelling method begins with the censored H I spectrum and a grid of η values. This grid runs from $\eta = 1$ to 10001, with the intervening grid value η_j defined as

$$\eta_j = \left(\frac{j\sqrt{10001} - 1}{1000} + 1 \right)^2, \quad (2)$$

where j runs from 0 to 1000. Using the definition of η (equation 1), this η grid is converted into a set of He II flux grids using complex H I fluxes. These He II fluxes are convolved with the *HST* COS Line-Spread Function creating a grid of *HST* resolution model spectra.

The η value in redshift bins ($\Delta z = 0.0003$) is given by the model spectrum that is the best match to the *HST* data. The size of the bins corresponds to ~ 1 pixel in G140L data and ~ 0.44 cMpc.

If either H I Ly α or He II Ly α is undefined for a given pixel, it is flagged to be ignored in later analysis. For our estimate of η , we selected the maximum redshift for HE 2347-4342 ($z = 2.85$) and for HS 1700 + 6416 ($z = 2.7$) to avoid proximity effects at ~ 3000 km s $^{-1}$. Our minimum redshift ($z = 2.4$ for HE 2347-4342 and $z = 2.16$ for HS 1700 + 6416) is driven by our requirement of S/N $\gtrsim 50$ per pixel in the optical spectra and by avoidance of the Ly β forest.

Our forward modelling gives a median η value of ~ 80 for HE 2347-4342 and ~ 167 for HS 1700 + 6416 for the redshift range of our final analysis. While this method addresses some of the issues for the direct determination of η , it still has some limitations. The largest source of uncertainty is the choice of continuum for the H I spectra (and to a lesser extent He II), which affects the estimated η (McQuinn & Worseck 2014). The combination of these effects limits the interpretation of the absolute values of η . We stress once more that, in this work, variation in η is key and the absolute values are not interpreted.

3.1 Filtering η on various scales

Our goal in this work is to investigate the strength and physical scale of UV background inhomogeneities. We applied a bandpass filtering to η and proceed to study O VI enrichment on various inhomogeneity scales in splits of the filtered field. In order to perform this filtering, we define the contrast in η (equation 3)

$$\delta\eta = \frac{\eta - \bar{\eta}}{\bar{\eta}}. \quad (3)$$

We used a Gaussian bandpass filter to extract the forward modelled $\delta\eta$ on various scales (R_s) in comoving megaparsecs (cMpc) using Planck 2015 cosmology evaluated at $z = 3$ (Planck Collaboration XIII 2016a).

Our Gaussian bandpass filter is created using a Gaussian function for the low-pass filter,

$$f_{G1}(x) = e^{-\frac{1}{2} \left(\frac{2x\sqrt{2\ln 2}}{R_l} \right)^2}, \quad (4)$$

(where R_l is the full width half-maximum low-pass scale) and a Gaussian function for the high-pass filter

$$f_{G2}(x) = e^{-\frac{1}{2} \left(\frac{2x\sqrt{2\ln 2}}{R_h} \right)^2} \quad (5)$$

(where R_h is the full width half-maximum high-pass scale). In both Gaussians, x is defined as the line-of-sight distance in comoving coordinates. The filtering scales were set by

$$R_h = R_s + 1 \text{ cMpc}, \quad R_l = R_s - 1 \text{ cMpc}. \quad (6)$$

The two Gaussians and the forward modelled η were then transformed into Fourier space $\hat{F}(k) = \mathcal{F}\{f(x)\}$ using the FFT command from the SCIPY FFTPACK PYTHON 3 package (Jones et al. 2001). The low-pass filter is simply the Fourier transform of f_{G1} ,

$$\hat{F}_{\text{low-pass}}(k) = \mathcal{F}\{f_{G1}(x)\}. \quad (7)$$

The high-pass filter is derived taking one minus the Fourier transform of f_{G2}

$$\hat{F}_{\text{high-pass}}(k) = 1 - \mathcal{F}\{f_{G2}(x)\}. \quad (8)$$

These filters were then multiplied with the Fourier space $\delta\eta$ and then inverse transformed back in to real space using the iFFT in the same package (equation 9),

$$\delta\eta_f(R_s) = \mathcal{F}^{-1}\{\mathcal{F}\{\delta\eta\} \hat{F}_{\text{low-pass}} \hat{F}_{\text{high-pass}}\}. \quad (9)$$

In forward modelling η , some pixels were undefined and these rare instances were interpolated over. Following the completion of the inverse Fourier transform, the pixels were then re-flagged as bad pixels. Additionally, the neighbouring pixels were also flagged in an effort to be conservative.

Fig. 2 shows the filtered eta contrast with some examples choices for the filtering scale for HE 2347-4342 and HS 1700+6416. The redshift range studied in our following analysis for HE 2347-4342 is 2.508 to 2.7 and for HS 1700 + 6416 is 2.295 to 2.66. The amplitude of $\delta\eta_f$ varies with z for HE 2347-4342. This appears to be a consequence of the varying noise in the He II forest. On 2 cMpc, this redshift dependence appears to be entirely driven by noise since the amplitude of $\delta\eta_f$ (2 cMpc) differs by two order of magnitude between the high S/N and low S/N paths. On larger scales, the varying signal amplitude seen may indeed be real or partly driven by noise. We do not attempt to explore this directly, instead we proceed under the assumption that we may meaningfully split the sample into two portions around the 50th percentile. If such a division is physically meaningful, a significant signal in O VI will be measured.

For $\gtrsim 20$ cMpc, absorption structure may become degenerate with quasar continuum variation and thus suppressed in a continuum fit. Therefore, scales larger than 20 cMpc along the line-of-sight are unreliable. On the other hand, on small scales ($\lesssim 1$ cMpc) thermal line broadening dominates (Fechner & Reimers 2007; McQuinn & Worseck 2014). Therefore, we conservatively limited ourselves to bandpass filtering scales in the range $2 \text{ cMpc} \lesssim R_s \lesssim 20 \text{ cMpc}$. However, as the resolution element of the *HST* COS G140L data corresponds to a scale of ~ 3 cMpc, structures in our 2 cMpc (1–3 cMpc) bin are somewhat suppressed.

This bandpass filtering allows us to direct our exploration of UV background to desired scales, while also suppressing the very large

or very small scales which may be dominated by systematic errors or undesirable physical effects.

4 PIXEL OPTICAL DEPTH

The pixel optical depth (POD) method is a pixel-by-pixel approach that searches for statistical excesses in metal absorption associated with Ly α absorption. Using this method, originally developed by Cowie & Songaila (1998), one determines the H I optical depth for Ly α forest pixels and pairs them with estimated apparent metal opacity at the same redshift by interpolating at the appropriate wavelength.

Here we will briefly summarize the key elements to the approach as applied to O VI absorption. For a detailed account of the method used see Aguirre, Schaye & Theuns (2002). Also see Cowie & Songaila (1998), Schaye et al. (2003), and Pieri & Haehnelt (2004) for discussion of the approach. O VI absorption resides fully within both the Ly α forest and the Ly β forest and is also affected by other Lyman series lines. Hence some effort must be made to minimize this contaminating absorption. To this end, the doublet nature of O VI absorption can be used to clean the sample of contaminating forest absorption. Here the optical depth is measured for both of the doublet lines, and then the lower equivalent optical depth is chosen (accounting for the difference in oscillator strength and wavelength) as the least contaminated measure. Furthermore, the pixel optical depth approach enables the search for metal lines even when the Ly α absorption is saturated and so the maximum Ly α opacity becomes unconstrained. One can recover a Ly α opacity measurement using the least contaminated among unsaturated higher order Lyman series lines (again correcting for differences in oscillator strength and wavelength). We apply this method using five Lyman series lines.

We selected a maximum POD analysis redshift of $z = 2.70$ for HE 2347-4342 to avoid its GP trough. This limit is a conservative cut, using the same buffer as used for the intrinsic quasar effects from the potential end of the GP trough at $z \sim 2.74$. In the case of HS 1700 + 6416 the maximum POD analysis redshift is $z = 2.66$ to avoid quasar proximity effects at $\sim 3000 \text{ km s}^{-1}$ plus a conservative buffer of three times the full width at half-maximum of our maximum scales. The minimum redshift in Ly α is limited to exclude quasar H I Ly β emission, but in practice the minimum redshift of our analysis is driven by the available O VI path (see below).

Armed with best estimates of opacity for the sample of Ly α and O VI pixel pairs, they are then binned by Ly α opacity and the median opacity for both Ly α and O VI in these bins were calculated. Hence the standard POD plot shows $\text{med}(\tau_{\text{O VI}})$ in bins of $\text{med}(\tau_{\text{H I Ly } \alpha})$. This is shown as a dashed line in Fig. 3. A significant correlation with a positive gradient indicates a measurement of correlated metal absorption (Pieri & Haehnelt 2004).

We adapted the method of splitting the POD sample used in Pieri, Schaye & Aguirre (2006). In that publication the authors split the sample into near/far regions from galaxies on 600 km s^{-1} scales using either directly observed as Lyman break galaxies or by the use of strong C IV absorption as a proxy. Here we split our sample of pixels by high/low η (among other comparisons) and go a step further by quantifying the ensemble difference in O VI opacity as outlined in Section 5. Error bars are estimated by bootstrap resampling the observed spectrum from 5 Å chunks. Following Pieri et al. (2006) we preserve information on whether pixel pairs fall into the high or low η sample in the process. At least 25 pixels from at least five unique chunks must be available for a given Ly α bin in order for us to report the measurement for that bin.

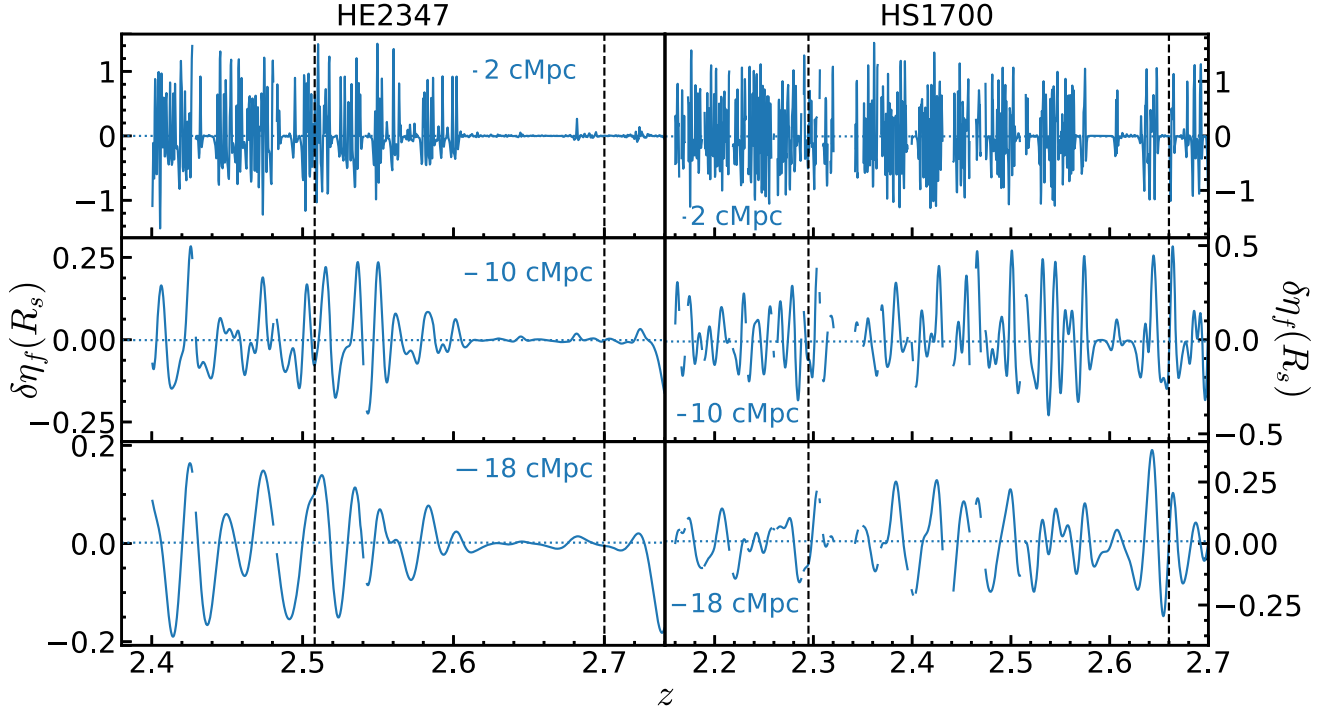


Figure 2. Examples of η contrast ($\delta\eta$) bandpass filtered on various scales for HE 2347-4342 (left-hand panel) and HS 1700 + 6416 (right-hand panel) for the redshift range analysed. The panels show (from top to bottom) $R_s = 2$ cMpc, $R_s = 10$ cMpc, $R_s = 18$ cMpc with the relevant scales marked in the caption as the blue line. The redshift paths used for O VI ($2.508 < z < 2.7$ for HE 2347-4342 & $2.295 < z < 2.66$ for HS 1700 + 6416) are indicated by the vertical dashed lines.

4.1 O VI as a tracer of ionizing flux

Various ions can be used to trace the ionizing flux levels at different redshifts. As shown in Agafonova et al. (2007, fig. 1), the ionization thresholds of different ions probe different portions of the meta-galactic ionizing spectrum. Using He II absorption as a proxy for UV hardening we can explore how metals are sensitive to associated shape changes in the UV background. Since O VI becomes more observable with strong UV hardening, we concentrated our efforts on its analysis. We further limited our minimum redshifts, from those noted above, to $z = 2.508$ for HE 2347-4342 and 2.295 for HS 1700 + 6416 to minimize continuum normalization uncertainty due to the presence of Lyman limit systems in the spectra and their associated Lyman limit breaks.

Fig. 3 shows the pixel optical depth search for O VI in subsamples split by high/low η filtered on three scales (2, 10, and 18 cMpc) for both quasars. For comparison the results of the combined all He II forest pixels POD analysis are also shown (dotted line). The red triangles show the results for the 50 per cent highest η pixels and the blue crosses show the POD analysis for the 50 per cent lowest η pixels. As can be seen in the middle panel for HE 2347-4342, O VI is sensitive on ~ 10 cMpc scales to this high/low η split. This demonstrates that large-scale UV background fluctuations, as identified by a filtered η field, can be probed and confirmed through the measurement of O VI absorption. This is evident on approximately 10 cMpc scales as observed in HE 2347-4342, but is not present on the smallest or largest scales that we can probe, nor is it seen in the analysis of HS 1700 + 6416. We will return to explore this latter point in Section 5.3. In the following section we will quantify potential differences in O VI optical depth, assess significance, and explore dependence on physical scale.

5 MEASURING THE DIFFERENTIAL OXYGEN OPACITY

To explore the difference in oxygen absorption between samples (including low and high η splits), we now define an extension to the standard POD approach for this specific purpose. We may calculate an O VI opacity difference

$$\Delta\tau_{\text{O VI}} \equiv \text{med}(\tau_{\text{O VI},S1}) - \text{med}(\tau_{\text{O VI},S2}), \quad (10)$$

where subscript $S1$ and subscript $S2$ refer to sample 1 and sample 2, respectively. Where necessary, sample 1 is the sample expected to reflect harder UV conditions and/or lower η . In the standard POD approach, the median metal opacity is calculated for a specified bin in $\tau_{\text{HI } Ly-\alpha}$. Rather than taking several bins in $\tau_{\text{HI } Ly-\alpha}$ as in the standard POD approach (shown in Fig. 3), we calculated $\Delta\tau_{\text{O VI}}$ for a single, wide bin reflecting the full range for which $\tau_{\text{HI } Ly-\alpha}$ is measurable. For each filtered scale, this is defined as the range of standard POD $\tau_{\text{HI } Ly-\alpha}$ bins that provide sufficient statistics to support a measure of $\tau_{\text{O VI}}$ in both samples. We utilize this broad $\tau_{\text{HI } Ly-\alpha}$ bin in order to simplify the estimation of uncertainty and to avoid unwanted weighting in the opacity difference measurement. The single bin approach is made possible by the fact that, in all the sample splits which follow, the difference in median $\tau_{\text{HI } Ly-\alpha}$ between the split samples is insignificant.

5.1 Splitting into high/low η samples

Here we calculate the O VI absorption difference for pixel samples split by high/low η for various filtering scales. Sample 1 in equation (10) refers to the low η sample and sample 2 is the high η sample. In Fig. 4, this $\Delta\tau_{\text{O VI}}$ is shown as a function of filtering scale for a

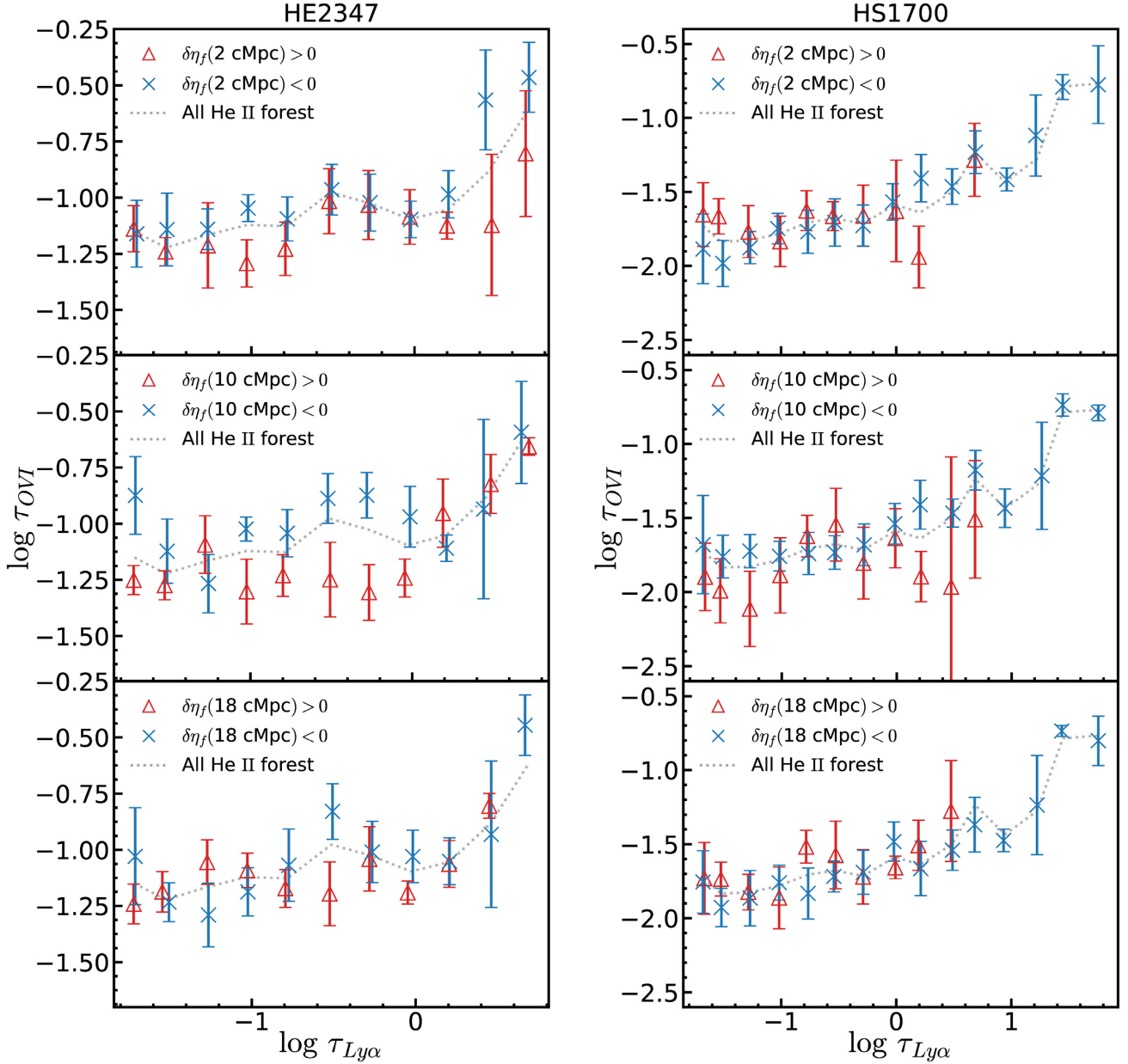


Figure 3. Pixel optical depth measurements for HE 2347-4342 (left-hand panel; $2.508 < z < 2.7$) and HS 1700 + 6416 (right-hand panel; $2.295 < z < 2.66$) with high-low $\delta\eta$ split on 2 cMpc (top), 10 cMpc (centre), and 18 cMpc (bottom). The high- η sample is indicated by the red triangles, and the low- η sample is indicated by the blue crosses. For comparison, the combined all He II forest POD results are indicated by the dotted lines. An O VI opacity difference is evident between samples associated with high and low η filtered on 10 cMpc scales for HE 2347-4342 only.

50:50 volumetric split. For HE 2347-4342, this difference peaks at a scale of 10 cMpc with an O VI excess $\Delta\tau_{\text{O VI}} = 0.032 \pm 0.017$ with a negligible corresponding difference in median $\tau_{\text{HI Ly}\alpha}$ between these samples (smaller than the standard POD analysis bin size), ruling out the null hypothesis of $\Delta\tau_{\text{O VI}} = 0$ at 2σ . This scale can be interpreted as a dominant scale of fluctuations, among the range of scales explored. In HS 1700 + 6416, there is no significant detection of a dominant fluctuation scale between 2 and 20 cMpc. This line-of-sight difference could be interpreted as a large-scale fluctuation, larger than can be assessed in a single line-of-sight (see Sections 5.3 and 6). Note that the mean redshift of the high and low η samples used in our pixel optical depth analyses are 2.61 and 2.60 for HE 2347-4342, and 2.49 and 2.50 for HS 1700 + 6416.

Therefore, any potential redshift evolution does not affect our results.

Thus far we have implicitly assumed, through our 50/50 split, that the hard UV background regions occupy an equal volume to soft UV background regions, but this need not be the case. We may relax this assumption and vary the relative proportions in the two samples. However, the value of such an exploration is limited by the fact that (as pointed out in Section 3), the amplitude of $\delta\eta_f$ is sensitive to the noise level of the He II forest. The special case of a 50/50 split is not vulnerable to this noise dependence (since a sign change in $\delta\eta_f$ will not occur as a result of varying amplitude), but other splits may result in systematic errors. With these caveats in mind, we have explored such differences in high/low η sample

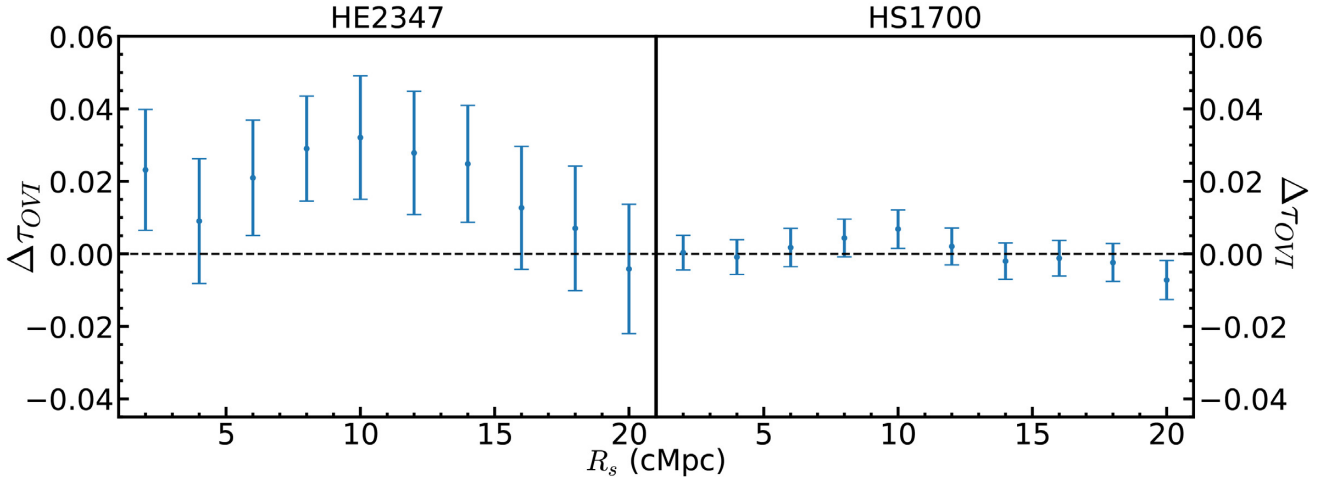


Figure 4. $\Delta\tau_{\text{O VI}}$ versus filtered scale R_s for HE 2347-4342 (left-hand panel; $2.508 < z < 2.7$) and HS 1700 + 6416 (right-hand panel; $2.295 < z < 2.66$), where $\Delta\tau_{\text{O VI}}$ is calculated using a 1 bin POD analysis, matching the standard POD bins with statistics in for both the high- and low- η samples. This shows a significant deviation for scales on the order of 10 cMpc for HE 2347-4342, and no significant deviation for HS 1700 + 6416.

sizes and find no significant difference from the 50/50 split results for either quasar. Hereafter, ‘high/low η ’ will refer only to a 50/50 high/low η split.

5.2 Null tests of high/low η splitting

In order to confirm that the signal we are seeing is genuine and not just an artefact, we conducted a pixel optical depth measurement at an offset of $\pm 1.5 \text{ \AA}$ from the O VI doublet (i.e. ~ 1030.5 and $\sim 1033.5 \text{ \AA}$). We initially chose this offset by selecting spectral regions thought to be bare of correlations identified in Pieri et al. (2014). We then performed the standard, all pixel, POD analysis to confirm that the POD did indeed return a null result for a single (all pixels) sample.

Fig. 5 shows the $\Delta\tau$ observable for the null offset for varying filtering scales. Our null result are, as expected, consistent with no signal. Therefore, we find that the signal that we see for O VI is real and not due to some artefact of the analysis procedure that impacts on local portions of the O VI forest.

5.3 Comparison of HE 2347-4342 and HS 1700 + 6416

In contrast to HE 2347-4342, HS 1700 + 6416 does not show a strong O VI opacity difference for high/low η splits. Additionally, when the O VI search for the entire He II forest of each quasar are compared (Fig. 6), HS 1700 + 6416 contains less O VI than HE 2347-4342. This holds true even if we shorten the search paths (285 cMpc for HE 2347-4342 and 538 cMpc for HS 1700 + 6416) to provide a matched redshift range (a path of 224 cMpc). Following the procedure outlined above for generating a single comparison $\tau_{\text{H I Ly}\alpha}$ bin, we measure $\Delta\tau_{\text{O VI}} = 0.070 \pm 0.012$ for the matched $2.508 < z < 2.664$ redshift path. The corresponding difference in median $\tau_{\text{H I Ly}\alpha}$ between these samples is negligible (smaller than the standard POD analysis bin size). This difference between lines-of-sight corresponds to a 6σ tension: considerably larger than what is seen between the high and low η samples shown above.

As the difference remains even with a matched redshift, we cannot attribute the difference seen in $\Delta\tau_{\text{O VI}}$ to a redshift difference. Rather it appears to be a difference in the UV background, with the

line of sight to HS 1700 + 6416 experiencing softer UV radiation than the line of sight to HE 2347-4342.

In addition to the differences seen in O VI opacity, there is also a difference seen in the median η values between the samples. As noted earlier, the median η is ~ 80 and ~ 167 for HE 2347-4342 and HS 1700+6416, respectively. This difference becomes slightly smaller with the matched redshift samples, with a median η for HS 1700 + 6416 of ~ 127 compared to ~ 74 seen in HE 2347-4342. This is significant and reinforces the apparently strong difference in ionization characteristics between these two lines of sight.

5.4 Comparison of O VI in the Gunn–Peterson trough and He II forest

HE 2347-4342 shows a substantial He II GP trough path (McQuinn 2009; Shull et al. 2010). It is interesting to compare our He II forest data with this GP data and in this section we show the comparison for HE 2347-4342 only. Section 6.2 widens the comparison to other samples used in this work and discusses evidence of progress towards complete He II reionization.

Fig. 7 shows the POD search for O VI absorption for the GP trough data ($2.7 \lesssim z \lesssim 2.85$; as defined in Section 2) and the entire analysis sample of He II forest data in the same spectrum. Also shown for comparison are our main subsamples from Section 5.1: 10 cMpc filtered η split 50/50. There is a clear difference in O VI opacity between the GP pixel sample and the entire HE 2347-4342 He II forest sample ($2.508 < z < 2.7$). Once more measuring this difference in O VI using our standard approach, we derive a measurement of $\Delta\tau_{\text{O VI}} = 0.038 \pm 0.012$. This is a 3σ significance measurement of opacity difference. The corresponding difference in median $\tau_{\text{H I Ly}\alpha}$ between these samples is negligible (smaller than the standard POD analysis bin size). The GP sample is marginally consistent with our high- η sample, and inconsistent with the low- η sample.

A limitation of the comparison here is the fact that there is a small but significant redshift difference between the GP trough and the He II forest ($\bar{z} = 2.60$ and $\bar{z} = 2.78$, respectively). Both metallicity evolution and the evolution in the mean flux decrement of the H I Ly α forest (which enters through residual uncorrected contaminating absorption in the O VI absorption band) could affect

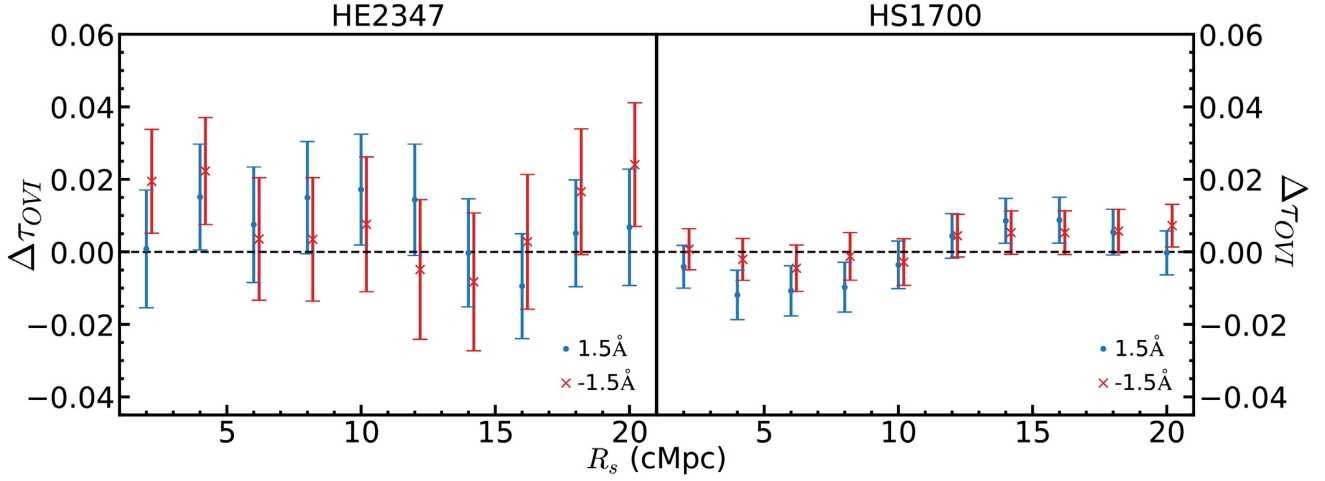


Figure 5. Null test sample of $\Delta\tau_{\text{OVI}}$ versus filtered scale (R_s in cMpc) for HE 2347-4342 (left-hand panel; $2.508 < z < 2.7$) and HS 1700 + 6416 (right-hand panel; $2.295 < z < 2.66$). The analysis was performed by modifying the restframe wavelength of the O VI with offsets of $\pm 1.5 \text{ \AA}$.

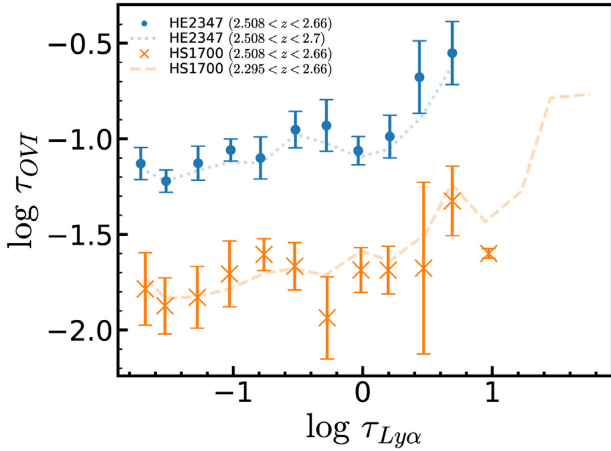


Figure 6. Comparison of all-pixel POD measurements of O VI for HE 2347-4342 and HS 1700+6416 showing that the difference in signal between the two lines-of-sight large and not due to a redshift dependence. The full path are as the faint lines (HE 2347-4342 as the blue dotted and HS 1700+6416 as the orange dashed), and the concordance redshift subsample is shown as the orange (HS 1700 + 6416) and blue (HE 2347-4342) points.

our results. However, both these effects are negligible as we argue in Section 6.

6 DISCUSSION

6.1 The scale of UV background fluctuations

In this work we have found significant large-scale differences in O VI opacity associated with fluctuations in η on $\gtrsim 5$ cMpc scales seen in the spectrum of HE 2347-4342. The O VI opacity differences peak at $\Delta\tau_{\text{OVI}} = 0.032 \pm 0.017$ on 10 cMpc scales and are significant at the 2σ level with a negligible corresponding difference in median $\tau_{\text{HI Ly}\alpha}$. We find no such signal in the spectrum of HS 1700 + 6416 despite the fact that the measurement precision is higher. However, there is an overall lack of O VI absorption seen in HS 1700 + 6416, which is inconsistent with the level of absorption seen in HE 2347-4342 at the 6σ level. The difference in O VI opacity between these 224 cMpc paths is $\Delta\tau_{\text{OVI}} = 0.070 \pm 0.012$ (2.2 times larger than

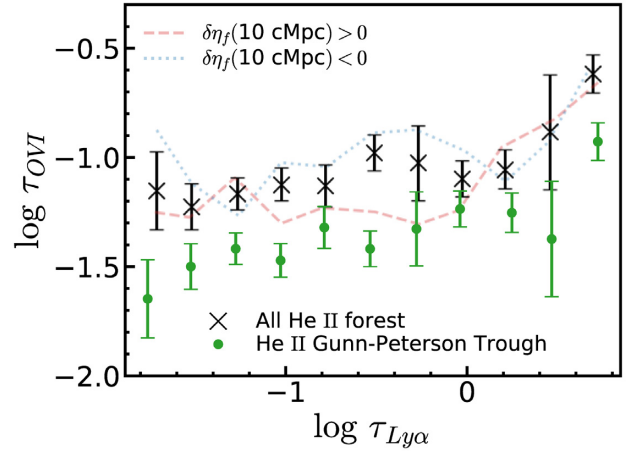


Figure 7. All POD measurements in the He II GP trough (green points; $2.7 \lesssim z \lesssim 2.85$, as defined in Section 2) as compared to the all He II forest pixel sample of HE 2347-4342 (black crosses; $2.508 < z < 2.7$) and the high (red line) and low (blue line) η ($2.508 < z < 2.7$) POD measurements previously shown.

the large scale difference measured within HE 2347-4342). This, combined with the overall higher value of η seen in HS 1700 + 6416, indicates that strong $\gtrsim 200$ cMpc UV background fluctuations exist at $z \approx 2.6$.

We limit ourselves to scales larger than 2 cMpc in order to avoid small-scale systematic effects associated with thermal line broadening (Fechner & Reimers 2007; McQuinn & Worseck 2014). Our measurements support the assertion that η probes real large-scale inhomogeneities in the UV background on several cMpc scales along the line-of-sight (e.g. Shull et al. 2004; Fechner & Reimers 2007). This is in direct contradiction to the case put forward by McQuinn & Worseck (2014) based on HE 2347-4342. In that work, they find weak η fluctuations consistent with spurious artefacts and find that their estimated η is fully consistent with a homogeneous UV background. We find the most likely explanation of this apparent conflict to be a dilution of their η signal due to an overestimate of the optical continuum in that work (a non-standard solution with essentially no pixels of the forest consistent with zero opacity). A systematic offset in the H I continuum could distort (and therefore

bias) the estimate of $\tau_{\text{H I}}$ to the extent where it is only weakly associated with the estimate of $\tau_{\text{He II}}$. In this scenario, the estimate of η of McQuinn & Worseck (2014) would be dominated by errors (thus resolving this conflict). If however, our recovery of high/low η regions is somewhat affected by noise, it could lead to an underestimate of this $\Delta\tau_{\text{O VI}}$.

In light of these significant doubts in the community about the degree to which η can be treated as a proxy for UV background fluctuations, it has been fundamental to our analysis that we can use O VI absorption to assess its physical significance. Moreover, we treat scale as a free parameter through bandpass filtering of η . In this context, our combined analysis of He II, H I, and O VI constitutes the first systematic measurement of UV background inhomogeneities as a function of scale in the post-helium-reionization Universe. We are not able to probe all the potential scales of UV background inhomogeneity, but assess particular windows in scale. We are able to study $2 \text{ cMpc} \leq R_s \leq 20 \text{ cMpc}$ and $\gtrsim 200 \text{ cMpc}$ scales. We do not attempt to measure η on line-of-sight scales larger than 20 cMpc due to concerns that the measured η variation will be sensitive to H I continuum normalization (analogous to how large-scale structures are not measured along lines-of-sight on these larger scales; e.g. Chabanier et al. 2018). Our results for the fiducial 50/50 case seem, on face value, to indicate that inhomogeneities in the UV background are seen at 10 cMpc and are not present on scales of 20 cMpc . However, it is possible that line-of-sight suppression of structure by continuum fitting plays a role erasing η fluctuations on scales as small as $\sim 20 \text{ cMpc}$. Hence, we do not consider the absence of fluctuations on 20 cMpc scales to be a reliable result.

Different lines-of-sight can be meaningfully compared since they are not susceptible to common continuum normalization systematic errors, again analogous to large-scale structure studies (e.g. Busca et al. 2013). Also large-scale filtering of η is not required. This allows the assessment of line-of-sight scale effects. Conservatively comparing a matched common redshift range between the two quasars equivalent to 224 cMpc , we find a large difference indicating strong inhomogeneities on these scales. This is effectively an integrated quantity since we cannot rule out that our measurement arises due to inhomogeneities on larger scales. Indeed, the entire path of HS 1700 + 6416 appears to be homogeneous within itself and is 538 cMpc in length.

Our results are consistent with a universe with $\geq 200 \text{ cMpc}$ regions characterized by their soft or hard UV background conditions. In this picture, the soft UV regions (HS 1700 + 6416) have little or no internal inhomogeneity on $2 \text{ cMpc} \leq R_s \leq 20 \text{ cMpc}$ scales. The hard UV regions on the other hand (HE 2347-4342) do show such inhomogeneity, peaked at 10 cMpc scales. This picture is consistent with all our results and, in particular, brings together our differing results from different quasar spectra without conflict.

Our results are not sensitive to rare strong O VI systems. Rare systems in any given Ly α opacity bin of the POD analysis would tend to inflate the bootstrap errors without modifying the estimated value. More common (but still minority) strong metal absorbers may create an apparent signal, but even in this case the bootstrap analysis would show inflated errors consistent with the true value of the opacity difference for the wider population. The statistical significance of our findings rule out this scenario. This is unsurprising since the POD analysis is itself outlier resistant through use of the median opacity, and its pixel-by-pixel approach is a volume average. The standard POD approach may be dominated by such systems for bins corresponding to saturated Ly α , but our use of single, wide Ly α opacity bins ensures that our measurements are driven by the majority weaker absorption.

An alternative interpretation of our high/low η splitting analysis must be considered, however. The observed effect could, in principle, be generated by $\gtrsim 5 \text{ cMpc}$ scale excesses in oxygen enrichment with simultaneous deficits in η . While it is possible that outflows could simultaneously increase enrichment and distort η , such scenarios seem implausible. Neither galactic outflows, nor AGN outflows above $z = 2$ have the right combination of extent, clustering, and incidence rate to generate coherent $\gtrsim 5 \text{ cMpc}$ scale excesses in enrichment for approximately half our low η sample (e.g. Pieri, Martel & Grenon 2007; Germain, Barai & Martel 2009). It is also by no means clear whether the corresponding structures in η are a consequence of such large regions of enhanced enrichment.

While no other study has systematically measured these scales, various studies provide a useful comparison. Worseck & Wisotzki (2006) and Worseck et al. (2007) find that η is sensitive to the presence of quasars at transverse separations of a few cMpc, which is consistent with our findings. HE 2347-4342 is one of the quasars used in these studies with known proximate quasars, but no quasars have been detected proximate to HS 1700+6416. This is consistent with our above findings that HE 2347-4342 shows systematically more hard UV photons and shows inhomogeneity, while HS 1700 + 6416 appears to be homogeneously soft. Also, Fechner & Reimers (2007) study large-scale η fluctuations in both HE 2347-4342 and HS 1700 + 6416 along with a small sample of strong C IV and O VI systems and find hints of a sensitivity to quasar proximity. Muzahid et al. (2011) also study small samples of C IV and O VI in the context of η and appeal to collisional ionization to interpret their results. In both cases, these works are focused on rare, strong absorbers and so are not directly comparable to our large-sample volumetric statistics.

Our measurement of large O VI opacity difference between the two lines-of-sight studied is motivated by our measurements of He II opacity. These results raise the question of whether line-of-sight to line-of-sight variance in O VI opacity have been previously seen in the literature even in the absence of He II Ly α forest information. While many spectra are available, no one has yet performed a directed analysis on the large-scale coherence length of metal absorption using the POD method. However, the raw POD results shown in fig. 7 of Aracil et al. (2004) do appear to show significant line-of-sight to line-of-sight variance at fixed redshift.

6.2 Probing the end of helium reionization with O VI absorption

HE 2347-4342 exhibits high redshift He II GP path (while HS 1700 + 6416 does not) and we take the opportunity to compare the O VI absorption in this path with other samples derived from these two spectra. In Section 5.4 we presented a comparison to He II forest data in HE 2347-4342 and found that the He II GP trough contains comparable O VI levels to that seen in the soft UV background (high η) sample. Here we place this GP trough data in a broader context among our measurements.

Fig. 8 combines all our O VI difference measurements and compares them to the scale of the difference associated with the He II GP. We apply once more our standard method for calculating the O VI opacity difference as set out in Section 5. For this calculation we use a common comparison sample. We select this sample to be the one that shows the hardest UV background conditions and so best reflects *an entirely complete He II reionization process*: the low η 50 per cent sample from HE 2347-4342 derived from filtering η on 10 cMpc scales. We designate this sample ‘hard UV background

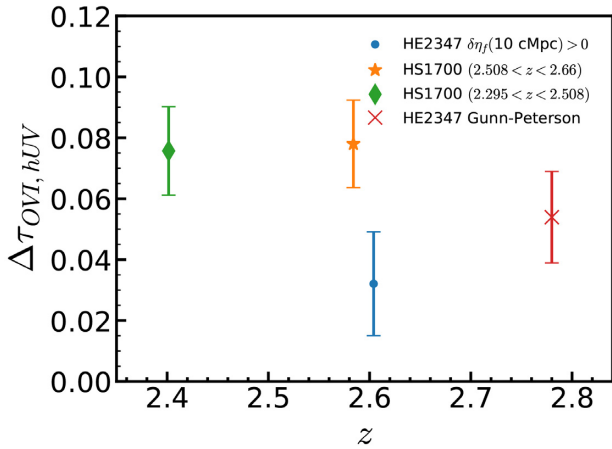


Figure 8. $\Delta\tau_{\text{OVI}}$ compared to an ‘entirely complete reionization’ reference sample (see the accompanying text). High values indicate strong evolution (and relatively weak O VI absorption in the sample in question). The hard UV background baseline is the 10 cMpc filtered low η HE 2347-4342 sample and this is compared with the 10 cMpc filtered high η sample (blue point; $2.508 < z < 2.7$), a high redshift HS 1700 + 6416 sample (orange star; $2.295 < z < 2.508$), a low redshift HS 1700 + 6416 sample (green diamond), and a sample drawn from the GP trough of HE 2347-4342 (red cross; $2.7 \lesssim z \lesssim 2.85$, as defined in Section 2).

sample’ and all measurements from this baseline are quoted as

$$\Delta\tau_{\text{OVI},hUV} \equiv \text{med}(\tau_{\text{OVI},HE,\eta_{\text{low}}}) - \text{med}(\tau_{\text{OVI},\text{other}}) \quad (11)$$

calculated in the manner described in Section 5, where $\tau_{\text{OVI},HE,\eta_{\text{low}}}$ is the baseline sample and $\tau_{\text{OVI},\text{other}}$ is the other sample indicated in the caption. It should be noted that, while we characterize this sample as ‘entirely completed reionization’, it is not our lowest redshift sample. Nor do we make any attempts to match redshifts (as we did in Section 5.3). Each sample simply uses this as a reference point for reionization progress. For HS 1700 + 6416 we use the narrow redshift comparison sample ($2.508 < z < 2.66$) and supplement this with the available lower redshift data ($2.295 < z < 2.508$). The choice to split the HS 1700+6416 data by redshift and not by filtered η is motivated by the result that splitting HS 1700 + 6416 pixels yields no significant O VI difference.

It is apparent in Fig. 8 that no trend towards harder UV background conditions or complete He II reionization is evident in O VI over this narrow, but pivotal redshift range. The most striking result is that the $\bar{z} \approx 2.78$ He II GP trough sample shows no sign of being more deviant from complete reionization than any other sample shown. Extended higher η paths such as those seen in a GP trough are expected to reflect softer UV background conditions. Given the magnitude of our measured O VI sensitivity to η outside the GP trough, one would expect a clear signal in O VI if this GP trough were associated with sharp UV background evolution associated with He II reionization. Instead the GP trough O VI absorption from HE 2347-4342 is statistically consistent with both the 10 cMpc filtered high η data from the same quasar and with HS 1700 + 6416 data despite having a much higher measured η than both (see Fig 1). Overall these results suggest that this He II GP trough does not trace a helium ionization phase change (see the following theoretical discussion).

A couple of minor caveats must be noted for completeness at this point. $\Delta\tau_{\text{OVI},hUV}$ for the red cross and the green diamond in Fig. 8 may include a contribution from evolution in metallicity or in contaminating forest absorption (Pieri & Haehnelt 2004).

Aguirre et al. (2008) show that the redshift evolution probed by the POD approach is weak and smaller than the variance for the small redshift difference here. Contaminating Ly α absorption can modify the measured apparent O VI opacity in the POD approach, but this also evolves more weakly (Kim et al. 1997, 2007; Faucher-Giguère et al. 2008) than the variance between samples. This is further compounded by the fact that the POD approach leaves only a weak residual contribution from forest contamination since efforts are made to reduce such contamination (as described in Section 4). Overall we find that both these potential systematic effects for the red cross and the green diamond in Fig. 8 are negligible.

6.3 Theoretical context

Our findings are broadly consistent with theoretical predictions of post-He II-reionization UV background inhomogeneities on $\gtrsim 10$ cMpc scales (e.g. Furlanetto 2009). Through calculations of the ionizing background and its connection to helium reionization, Faucher-Giguère et al. (2009) found that the mean free path of He II ionizing photons should be in range of ~ 15 –600 cMpc. Davies et al. (2017) combined this with their analytic calculation of η to perform 3D semi-analytic models of the helium ionizing background. In doing so they put forward a scenario where 200–300 cMpc UV background inhomogeneities and realistic $z < 3.2$ GP troughs occur without appealing to He II reionization. Our results favour this scenario.

These findings have a role in a broader context with implications for the source populations of the UV background and their evolution reaching back to hydrogen reionization. The recent Planck measurements of the opacity of free electrons (Planck Collaboration XLVII 2016b) indicate a relatively late phase of hydrogen reionization, raising the possibility that quasars might be responsible for some or all of this process (Madau & Haardt 2015; Mitra, Choudhury & Ferrara 2018; Garaldi, Compostella & Porciani 2019). Indeed the measured inhomogeneity in H I absorption at end of hydrogen reionization may require that rare sources such as quasars play an important role (Chardin, Puchwein & Haehnelt 2017; Becker et al. 2018; D’Aloisio et al. 2018). Furthermore, there has been discussion in the literature of a hitherto unidentified faint and high redshift quasar population (Giallongo et al. 2015; Matsuoka et al. 2018). The prospect of an early and extensive contribution from quasars driven by these factors has the potential to conflict with He II GP measurements (Garaldi et al. 2019). While tuned models can bring into agreement He II reionization and a significant early post-H I-reionization role for quasars (Mitra et al. 2018), a weakening of the perceived connection between He II GP troughs and He II reionization would also ease the apparent tension. Our results of He II GP trough data (studied in the broader context of O VI and its association with UV background fluctuations) favour this weakening of the connection to He II reionization.

7 CONCLUSION

We have combined He II and H I Ly α forests, through the ratio η , along with pixel optical depth measurements of O VI to search for large-scale inhomogeneities in the extragalactic UV background in the sightlines towards HE 2347-4342 and HS 1700 + 6416. Additionally, we have compared the He II forest lines-of-sight, and the Gunn–Peterson trough in HE 2347-4342, to search for larger scale inhomogeneities and examine the end of He II reionization. We can summarize our results as follows.

(i) O VI opacity is sensitive to η variation filtered on large scales ($\gtrsim 5$ cMpc).

(ii) Variation in η filtered on large-scales can probe the UV background and is not overwhelmed by observing noise and systematic errors.

(iii) On ~ 10 cMpc scales (probed by η variation) the UV background varies such that associated median O VI opacity differs by $\Delta\tau_{\text{O VI}} = 0.032 \pm 0.017$.

(iv) On $\gtrsim 200$ cMpc scales (comparing lines-of-sight) the UV background varies such that associated median O VI opacity differs by $\Delta\tau_{\text{O VI}} = 0.070 \pm 0.012$.

(v) O VI absorption associated with the He II Gunn–Peterson trough in HE 2347-4342 differs from the He II forest of the same quasar by $\Delta\tau_{\text{O VI}} = 0.038 \pm 0.012$ and is broadly consistent with the high η (soft UV background) path for the same quasar.

(vi) O VI absorption associated with the Gunn–Peterson trough shows no evolution when compared with samples thought to represent (more) complete He II reionization at lower redshifts, suggesting that this He II Gunn–Peterson trough does not trace a sharp He II reionization phase change.

Overall we find that our analysis favours large-scale (~ 10 cMpc and $\gtrsim 200$ cMpc) UV background fluctuations consistent with recent theoretical projections. Our results are suggestive of extended soft/hard UV background regions, with hard regions showing significant internal inhomogeneities on ~ 10 cMpc scales, but soft UV regions lacking such structure. We find no evidence of a contribution from He II reionization in our $z < 3$ sample (despite the presence of a Gunn–Peterson trough). There are no detailed projections of the magnitude of expected O VI opacity difference with which to compare and so we provide our measured opacity differences to enable the community to compare our results with simulations.

Given the limited number He II quasars sufficiently bright for POD analysis, the prospects to significantly extend this analysis to larger data sets are not promising. However, we have established that O VI opacity measured over large coherent paths in the $z \sim 3$ Ly α forest can usefully probe the UV background. Therefore the potential exists to use large-scale O VI inhomogeneity as a proxy for UV background fluctuations, in the absence of He II information. The prospects for direct detection of large volumes of the IGM proximate to transverse quasars is encouraging given the increasing number density and completeness of quasars in recent massive spectroscopic surveys Baryon Oscillation Spectroscopic Survey (BOSS; Dawson et al. 2013) and extended-BOSS (eBOSS; Dawson et al. 2016), and future surveys WEAVE-QSO (Pieri et al. 2016) and Dark Energy Spectroscopic Instrument (DESI; DESI Collaboration 2016). Metal absorption and its sensitivity to UV background fluctuations due to detected quasar placement may be probed using stacking methods (Pieri et al. 2014) and modified pixel optical depth methods (Pieri et al. 2010) in these large and growing surveys.

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