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Re-examining the case for neutral gas near the redshift 7 quasar ULAS J1120+0641

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ABSTRACT

Signs of damping-wing absorption attenuating the Lyman α emission line of the first known $z \sim 7$ quasar, ULAS J1120+0641, recently provided exciting evidence of a significantly neutral intergalactic medium (IGM). This long-awaited signature of reionization was inferred, in part, from a deficit of flux in the quasar's Lyman α emission line based on predictions from a composite of lower redshift quasars. The composite sample was chosen based on its C IV emission line properties; however, as the original study by Mortlock et al. noted, the composite contained a slight velocity offset in C IV compared to ULAS J1120+0641. Here we test whether this offset may be related to the predicted strength of the Lyman α emission line. We confirm the significant (∼10 per cent at rms) scatter in Lyman α flux for quasars of a given C IV velocity and equivalent width found by Mortlock et al. We further find that among lower redshift objects chosen to more closely match the C IV properties of ULAS J1120+0641, its Lyman α emission falls within the observed distribution of fluxes. Among lower redshift quasars chosen to more closely match in C IV velocity and equivalent width, we find that ULAS J1120+0641 falls within the observed distribution of Lyman α emission line strengths. This suggests that damping-wing absorption may not be present, potentially weakening the case for neutral gas around this object. Larger samples of $z > 7$ quasars may therefore be needed to establish a clearer picture of the IGM neutral fraction at these redshifts.

Key words: intergalactic medium – quasars: emission lines – quasars: individual: J1120+0641 – cosmology: observations – dark ages, reionization, first stars.

1 INTRODUCTION

The reionization of hydrogen in the intergalactic medium (IGM) is believed to coincide with the buildup of the first galaxies. Determining when and how the IGM became ionized can therefore deliver unique insights into the earliest epochs of galaxy formation. Evidence from the Lyman α forest in high-redshift quasars indicates that the process largely finished by $z \sim 6$ (Fan et al. 2006; Becker, Rauch & Sargent 2007). While the exact timing remains unknown, the recent *Planck* results (Planck Collaboration XIII 2015) favour models of late reionization, which motivates the observational search for signs of reionization.

The recent discovery of the most distant quasar known, ULAS J1120+0641 (Mortlock et al. 2011), with a redshift of 7.0842 ± 0.0004 (Venemans et al. 2012), provides a unique opportunity to probe the epoch of reionization at a time when the process was potentially just ending. As noted by Mortlock et al. (2011), this object exhibits strong absorption on the blue side of its Lyman α emission line. The red side of its Lyman α line may also be somewhat weaker than expected based on the strength of its other emission lines, notably C IV. These traits have jointly been interpreted as evidence for neutral gas in the vicinity of ULAS J1120+0641, with the weak Lyman α line being due to damping-wing absorption extending to $\lambda_{\rm rest} \geq 1216$ Å. In a scenario where the neutral gas is intergalactic, models of the quasar's proximity zone suggest that the surrounding IGM may be ≥10 per cent neutral (Bolton et al. 2011). The lack of intervening metal absorption lines further suggests that any neutral gas would have to be highly metal poor, particularly if it is confined to a discrete absorber (Simcoe et al. 2012).

The case for neutral gas in the vicinity of ULAS J1120+0641, whether localized or intergalactic, depends strongly on the reality of the damping-wing absorption. A truncated proximity zone, while unusual, could be due to an optically thick ($N_{\rm H\,I} \gtrsim 10^{17}$ cm^{-2}) absorber in the vicinity of the quasar, but a damping wing requires a large column density ($N_{\rm H\,I} \gtrsim 10^{20}$ cm^{-2}) of neutral gas. A

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challenge in analysing such high-redshift quasars, however, is that their intrinsic spectra, including their Lyman α emission lines, exhibit significant variation between objects. This combined with the fact that the blue side of Lyman α is often strongly affected by Lyman α forest absorption (generally arising from ionized gas) means that the intrinsic shape of Lyman α is largely unknown a priori. This makes it difficult to estimate the extent to which the emission line flux has been absorbed, and in the case of ULAS J1120+0641, whether damping-wing absorption may be present.

One approach to resolving this issue has been to estimate the intrinsic quasar spectrum near Lyman α using either principal component analysis (PCA; Sukuzi et al. 2005; Paris et al. 2011) or composites made from lower redshift objects (e.g. Vanden Berk et al. 2001; Cool et al. 2006). The general approach is to find lower redshift quasars whose spectra match the object of interest redwards of Lyman α. The spectra of the lower redshift objects, which are less affected by Lyman α forest absorption, can then be used to predict the unabsorbed continuum around the Lyman α emission line and over the forest. This was the approach taken by recent studies of ULAS J1120+0641 (Mortlock et al. 2011; Simcoe et al. 2012). In these cases the composite was constructed primarily to match the C IV emission line, whose properties are known to correlate with those of Lyman α (Richards et al. 2011).

The fidelity of a composite match will naturally depend on the availability of similar objects at lower redshifts. However, the C IV line of quasars exhibits a source systematic velocity shift (Richards et al. 2002; Shang et al. 2007) which is usually attributed to the presence of strong winds and jets associated with the quasar (Proga, Stone & Kallman 2000). In addition, the equivalent width (EW) of the C IV line is known to correlate with EW of Lyman α. Mortlock et al. 2011 match ULAS J1120+0641 by selecting objects based on their C IV EW and blueshift, but acknowledge that this is complicated by the fact that ULAS J1120+0641 has a large C IV blueshift and is matched by relatively few lower-z objects. The sparsity of suitable objects is aggravated by the need to restrict the selection to objects within the narrow redshift range $2.3 \lesssim z \lesssim 2.6$ chosen to minimize the impact of Lyman α forest absorption. A compromise thus had to be made in order to obtain a large enough sample of objects, resulting in a small misalignment in C IV blueshift between the composite and ULAS J1120+0641's spectrum. In this paper, we examine whether the difference in blueshift, although small, might be having an unanticipated effect on the predicted strength of the Lyman α emission line.

2 METHODS

We aim to predict the strength of the Lyman α emission line without making use of a composite spectrum. Our approach is to select two samples of lower redshift quasars solely on their C IV emission properties, regardless of how rare they may be. One sample is designed to contain objects similar to ULAS J1120+0641 in C IV properties, except with a small blueshift mismatch; the objects in the second sample are chosen to display no such offset. We then measure the Lyman α flux strength for all objects, which allows us to establish the rarity of quasars with Lyman α emission intrinsically as weak as in ULAS J1120+0641 in both samples.

Our sample of comparison spectra is drawn from the Sloan Digital Sky Survey (SDSS) Data Release 7 (DR7) quasar catalogue (York et al. 2000; Ochsenbein, Bauer & Marcout 2000). The DR7 catalogue contains 10 871 objects in the range $2.4 \leq z \leq 4$, where both the Lyman α and C IV emission lines are in the observed wavelength range. DR7 was chosen because of the availability of high-quality redshifts measured by Hewett & Wild (2010). In this work, we use only objects where the systemic redshift was determined primarily from the C III] emission line complex. These redshifts were used to shift the spectra into the rest frame, and for assessing the relative blueshift of the C IV line.

Similarly to Mortlock et al. (2011), we selected sub-samples of quasars based on their C IV rest-frame EW, $W_{\mathrm{C\,IV}}$, and velocity shift relative to systemic, $\Delta v_{\mathrm{C\,IV}}$. We do not attempt to provide an absolute value of ULAS J1120+0641's C IV line blueshift, as doing so requires more careful treatment of the underlying continuum as well as nearby emission lines, in particular Fe II. For an up-to-date value, see De Rosa et al. (2014). Since the ultimate goal is to identify objects with properties similar to ULAS J1120+0641, we used the ULAS J1120+0641 C IV emission line itself as a basis for the classification. Using the combined Focal Reducer/low dispersion Spectrograph 2 (FORS2) and Gemini Near-Infrared Spectrograph (GNIRS) spectrum presented by Mortlock et al. (2011), we fit the ULAS J1120+0641 C IV line over the wavelength range $1435 < \lambda_{\mathrm{rest}} < 1640$ Å using two components, a power-law fit over $1435 < \lambda_{\mathrm{rest}} < 1480$ Å and $1580 < \lambda_{\mathrm{rest}} < 1640$ Å, plus a spline, fit by hand, to the emission line flux in excess of the power law shown in Fig. 2. We then fit each object in the DR7 catalogue over the same wavelength range using a power law plus an emission line template based on the ULAS J1120+0641 spline. The emission line fit, normalized by the power-law continuum, is given by

$$F_{\mathrm{C\,IV}}(\lambda') = a F^{1120}_{\mathrm{C\,IV}}(\lambda)\,, \tag{1}$$

where $F^{1120}_{\mathrm{C\,IV}}$ is the ULAS J1120+0641 emission line fit, normalized by its power law, and a is a scaling factor. The rest-frame wavelengths are related as

$$\lambda' = \lambda\left(1 + \frac{\delta v}{c}\right)\left[1 + s\frac{(\lambda - 1540\,\text{Å})}{\lambda}\right]\,, \tag{2}$$

where δv is the velocity shift of the C IV line relative to ULAS J1120+0641, and s is a stretch factor about 1540 Å, which lines near the peak of the C IV line in ULAS J1120+0641. Nominally, objects with C IV lines that are well matched to ULAS J1120+0641 will have $a \simeq 1$, $\delta v \simeq 0$ and $s \simeq 0$. Given these parameters, $W_{\mathrm{C\,IV}}$ for each object as a fraction of that of ULAS J1120+0641 can then be recovered by $W_{\mathrm{C\,IV}}/W^{1120}_{\mathrm{C\,IV}} = a(1 + s)$.

Fig. 1 shows the resulting C IV emission parameter space for 7025 SDSS quasars over $2.4 \leq z \leq 4.0$ for which spectra with Hewett & Wild (2010) C III] redshifts were available. As noted by Mortlock et al. (2011), the ULAS J1120+0641 C IV emission line appears to be highly blueshifted compared to the general population of quasars. This makes it fall at the edge of the usual distribution of C IV parameters.

We proceeded to select one sample of objects located close to ULAS J1120+0641 in C IV parameter space, and another sample with the C IV blueshift offset from the nominal value by ~3 Å (~600 km s^{-1}). This offset is chosen to mimic the apparent offset in C IV between the ULAS J1120+0641 spectrum and the composite fit of Mortlock et al. (2011), as shown in Fig. 2. The cuts we used are shown in Table 1.

A cut of SNR ≥ 5 per pixel, measured by making use of the associated SDSS error arrays over the wavelength range 1450–1500 Å, was also applied in the interest of measurement accuracy. For comparison the GNIRS spectrum of ULAS J1120+0641 has $\mathrm{SNR}_{\mathrm{J1120}} \sim 14$ per velocity bin over the same range. This initial cut yielded unrefined samples consisting of 204 C IV-matched quasars and 709 offset quasars. Due to the large uncertainties in the values

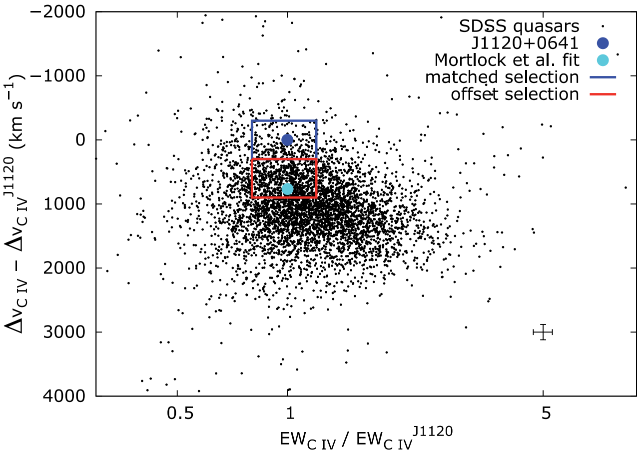

Figure 1. C IV EW–blueshift anomaly diagram showing the C IV emission properties of 5207 SDSS quasars in black and ULAS J1120+0641 in blue. This includes all DR7 quasars in the range $2.4 < z < 4$ for which spectra with SNR > 5 were available. Error bar in the bottom-right corner is representative for points located in the middle of the distribution; scatter in extreme values is due to objects whose C IV line is not well modelled by the spline fit, such as broad absorption line quasars. Thick lines: initial cuts from which the matching (blue) and offset (red) selections were extracted (see text). The location of the composite quasar spectrum from Mortlock et al. (2011) is shown in light blue.

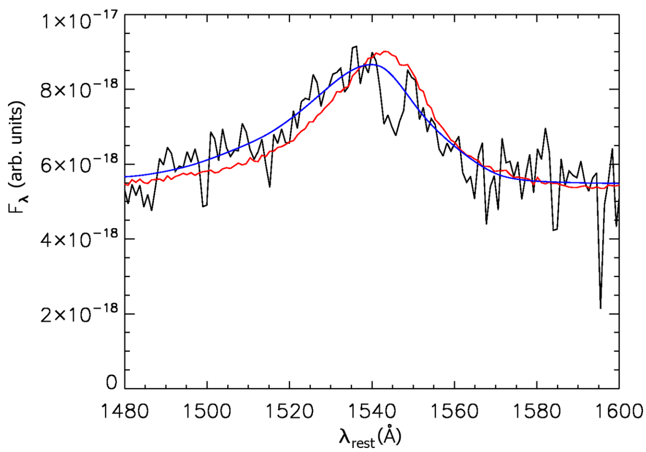

Figure 2. Black: C IV emission line of ULAS J1120+0641 from GNIRS spectrum. Red: composite quasar spectrum from Mortlock et al. (2011). Blue: spline fit to ULAS J1120+0641's C IV emission line. The distance between the peaks of the fits is ~3 Å in the rest frame of the quasar, corresponding to a velocity offset of ~600 km s^{-1}.

Table 1. Selection criteria for our initial C IV emission line cuts. The matching selection is chosen to match the C IV emission of ULAS J1120+0641 as well as possible. The offset selection is chosen to mismatch ULAS J1120+0641's C IV emission line blueshift by 600 km s^{-1} or about 3 Å.

Selection	$EW_{C\,IV}/EW_{C\,IV}^{J1120}$	$\Delta v_{C\,IV} - \Delta v_{C\,IV}^{J1120}$
Matching	0.8–1.2 Å	−300 to 300 km s^{-1}
Offset	0.8–1.2 Å	300–900 km s^{-1}

of EW and blueshift for the objects in our sample, we expected the initial cuts to be inefficient at finding all of, and only, excellent matches for ULAS J1120+0641's C IV emission. For this reason, the initial selection boxes are large and a second, manual cut was necessary to refine the selection.

Next, each object's C IV emission line was overlaid with ULAS J1120+0641's C IV emission line and similarity was evaluated visually. Objects which displayed too much or too little line asymmetry, as well as those whose C IV emission peak was visually offset from ULAS J1120+0641's corresponding value, were rejected and excluded from the sample. This yielded a refined sample of 111 objects which closely matched ULAS J1120+0641's C IV emission. The same process was repeated for the C IV-offset sample, yielding a refined sample of 216 objects with a C IV blueshift offset. The mean redshifts for the matched and offset selections were $z = 2.877$ and $z = 2.912$, respectively, while the median values were $z = 2.898$ and $z = 2.937$, respectively. A two-sided Kolmogorov – Smirnov test revealed no evidence that the two samples had been drawn from different distributions ($p > 0.10$).

Measuring the intrinsic Lyman α flux is particularly difficult for our samples since they include quasars with redshifts as high as $z = 4$, for which Lyman α forest absorption is a greater issue. This is further complicated by the complex shape of the Lyman α emission line over this range, which includes contributions from asymmetric Lyman α emission as well as NV. For these reasons, the mean unabsorbed continuum in each object was estimated over the range 1216–1220 Å, which was chosen to maximize our sensitivity to the Lyman α emission strength, while minimizing the impact of Lyman α forest absorption. Even in this wavelength range, however, Lyman α and metal absorption lines can potentially obscure the intrinsic continuum, particularly at higher redshifts. We therefore inspect each object visually and estimate the continuum by eye, accounting for absorption lines to the extent possible. This will naturally be an imperfect process; however, the errors in the continuum estimate arising from absorption lines are expected to impact both samples equally. To mitigate any bias caused by manual measurement, we measured the two samples together with the objects in random order. As a further check, we calculate the mean spectrum of the two samples without attempting to correct for absorption lines (see below).

Emission line fluxes for each object were calculated as a fraction of the underlying power-law continuum. The flux of each object was normalized by measuring the mean flux over the wavelength range 1450–1500 Å and the continuum emission was modelled by a power law fitted iteratively over narrow, emission line free regions of the spectrum. These fitting windows spanned the rest wavelength ranges 1320–1350 Å, 1435–1480 Å and 1600–1700 Å. The range 2000–2050 Å was used in addition for $z \leq 3$ objects for which those wavelengths were present in the rest frame. The peak flux over C IV was measured by the same method for all objects as well as ULAS J1120+0641 to check that the C IV emission was well matched by our selections and to ensure that direct comparison with the flux value over the Lyman α red wing was meaningful.

3 RESULTS AND DISCUSSION

Among the objects which matched the C IV emission in shape and EW but which were offset in blueshift by ~600 km s^{-1}, only three per cent of objects showed Lyman α emission weaker than ULAS J1120+0641 over the same range (Fig. 3). This is consistent with the assessment by Mortlock et al. (2011) that ULAS J1120+0641 is

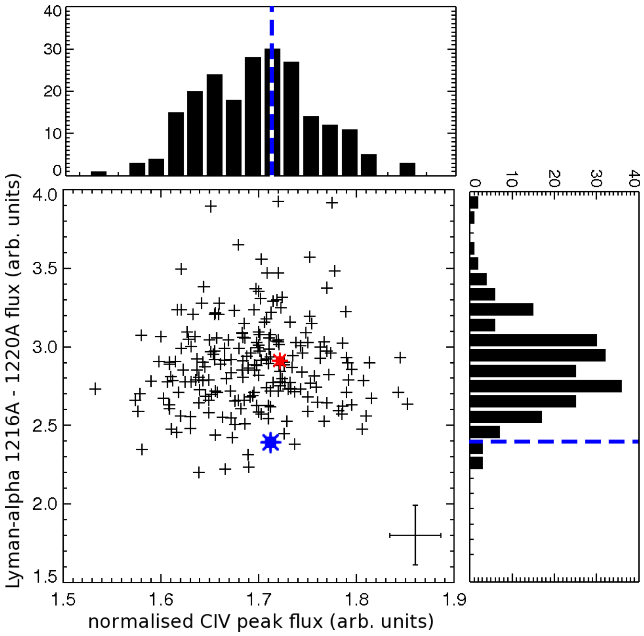

Figure 3. Comparison of C IV peak flux and Lyman α red-wing flux for 216 quasars matching ULAS J1120+0641 in C IV EW and offset from ULAS J1120+0641's correct C IV blueshift value by ~600 km s^{-1}, drawn from the red box in Fig. 1. ULAS J1120+0641's location is shown by a thick blue star. Red star indicates the location of the Mortlock et al. (2011) composite quasar spectrum when measured in the same way. The Lyman α red-wing flux is measured between 1216 and 1220 Å. Among this population ULAS J1120+0641 is a 97 per cent outlier in Lyman α red-wing flux. Representative error bar shown in the bottom-right corner.

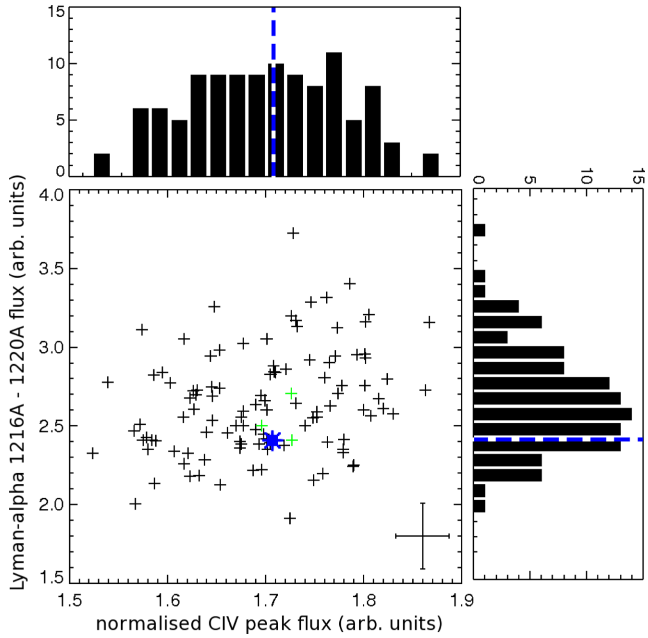

Figure 4. Comparison of C IV peak flux and Lyman α red-wing flux for 111 quasars matching ULAS J1120+0641's C IV emission in both EW and blueshift, drawn from the blue box in Fig. 1. ULAS J1120+0641's location is shown by a thick blue star. The objects highlighted in green are shown in Fig. 6. The Lyman α red-wing flux is measured between 1216 and 1220 Å. Among this population, 31 per cent of objects have Lyman α lines that are weaker than ULAS J1120+0641. Representative error bar shown in the bottom-right corner.

an ~2σ outlier from the composite they used. In contrast, among the selection which matched ULAS J1120+0641 in C IV emission, we find that 31 per cent have Lyman α emission over the red wing weaker in magnitude than ULAS J1120+0641 (Fig. 4). In addition, our C IV measurements are shown to demonstrate no residual correlation in these small samples ($R_{\rm matched} = 0.20$, $R_{\rm offset} = 0.07$), demonstrating that the C IV emission line of ULAS J1120+0641 is typical among these samples. We therefore find no compelling evidence that the Lyman α flux of ULAS J1120+0641 is anomalously low.

The averages and 68 (95) per cent bounds in Lyman α flux values for the matched and offset sample are $F_{\rm L\alpha} = 2.64^{+0.29}_{-0.32}\left(^{+0.63}_{-0.50}\right)$ and $F_{\rm L\alpha} = 2.88^{+0.17}_{-0.32}\left(^{+0.60}_{-0.52}\right)$, respectively, corresponding to variations of ~±10 (~± 20) per cent in both distributions. These values are similar to the corresponding value of 13 per cent quoted by Mortlock et al. (2011) for the spread in Lyman α flux once C IV blueshift is constrained; however the distributions are mildly non-Gaussian since they have a tail and those numbers are given as a consistency check only. In addition, these values of the spread are given at a particular wavelength.

Small sample size, low SNR and scatter mean that our sample might not be suitable for making an appropriate composite fit to ULAS J1120+0641, and such an analysis is beyond the scope of this work. Fig. 5 presents the average spectrum for both our selections; those were made by interpolating the spectra on to a common wavelength array and taking the mean value pixel-by-pixel. The spectra were power-law corrected and normalized but absorption was not addressed. The difference in flux between the peaks of the average spectra in Fig. 5 is comparable to the difference between the averages of the distributions in Figs 3 and 4; however, the effect of absorption is to weaken the emission feature in the average spectra. This confirms the fact that a small mismatch in the C IV emission line can have a significant effect on Lyman α emission. Although this effect is not large, it is sufficient to significantly impact the degree to which ULAS J1120+0641 is an outlier. The amount by which the average spectra differ in C IV blueshift is similar to the mismatch between ULAS J1120+0641 and its composite fit as published in Mortlock et al. (2011), condoning our use of the value of a ~600 km s^{-1} C IV blueshift mismatch.

Example objects matching ULAS J1120+0641's spectrum extremely well over its entire continuum and down to the onset of the Lyman α forest at 1216 Å are shown in Fig. 6 along with their respective redshifts. Using the strength of flux right of 1216 Å in a manner similar to ULAS J1120+0641, one would thus falsely infer the presence of a damping wing in those objects. A large variety of Lyman α peak shapes exists among the objects which match ULAS J1120+0641's C IV line; in particular the N V emission line at 1240 Å overlaps with Lyman α in a non-trivial way especially when the latter is weak. We make no attempt to constrain the N V emission. The majority of objects in our sample display a visible Si II emission line at 1260 Å, suggesting that the high-ionization lines C IV, N V and Lyman α are blueshifted together while low-ionization lines Si II, O I, C II are not. Our findings are in agreement with Richards et al. (2011) who identify a link between a large N V/Lyman α ratio in quasars with extreme C IV blueshifts as well as a possible C IV blueshift/Lyman α blueshift correlation. This effect also helps to resolve the apparent mismatch of N V in the Mortlock et al. (2011) composite.

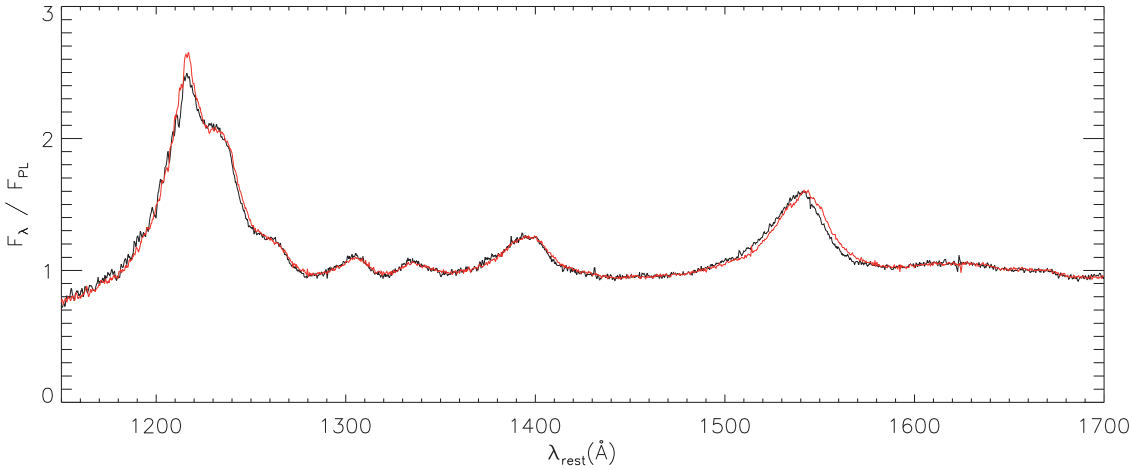

Figure 5. Average spectra of the matched selection of quasars (black) and the offset selection (red). Note how a small mismatch in the C IV emission line leads to large variation of the Lyman α peak flux, while the low ionization lines are not affected. The spectra were normalized by dividing by a fitted power law; absorption was not taken into account and as a consequence these averages do not represent the underlying continuum emission. Uncorrected absorption tends to both lower and smooth the peaks hence the difference in mean spectra is less pronounced than in the ensemble distributions (see Figs 3 and 4).

4 CAVEATS

We have argued that the scatter in Lyman α flux for a given C IV EW, combined with a small decrease in Lyman α flux with increasing C IV blueshift, is sufficient to bring the red wing of the Lyman α line of ULAS J1120+0641 within the distribution seen in lower redshift objects. Reconstructing the unabsorbed continuum of a quasar is known to be a challenging problem, however (e.g. Paris et al. 2011, and references therein), and it is important to bear in mind certain caveats. For example, accurate measurements of C IV blueshifts require reliable estimates of the systemic quasar redshifts. For the comparison SDSS spectra, we have used redshifts based on C III] from Hewett & Wild 2010, assuming that these are independent from the C IV and Lyman α properties. The C III] feature is a blend of Al III, Si III and C III] emission, however (e.g. Vanden Berk et al. 2001), and so the measured redshift will depend on the relative strengths and velocity shifts of these components. If the properties of this emission complex correlate with the properties of the C IV and/or Lyman α lines, then this may introduce systematic biases into the relationship we infer between C IV and Lyman α.

As noted earlier, the ULAS J1120+0641 redshift is measured from [C II] 158 μm emission from the interstellar medium of the host galaxy (Venemans et al. 2012). There is some indication, however, that C III] in ULAS J1120+0641 is slightly blueshifted with respect to [C II] (see fig. 1 of Mortlock et al. 2011). If this is generally true for quasars with large C IV blueshifts, then we should potentially adopt the C III] redshift for ULAS J1120+0641 when comparing it to objects with redshifts derived from C III]. This would give a smaller relative blueshift for C IV in ULAS J1120+0641, meaning that our comparison objects should be drawn from a region closer to the red box in Fig. 1. By the arguments presented here, this would imply a somewhat higher expected intrinsic Lyman α flux over 1216–1220 Å. On the other hand, the observed wavelength at which discrete Lyman α forest absorption begins in ULAS J1120+0641, i.e. the shortest wavelength at which a smooth damping could be detected, would correspond to a longer rest-frame wavelength, and hence a weaker portion of the Lyman α emission line profile. It is therefore unclear whether adopting a lower redshift for ULAS J1120+0641 would strengthen the case for damping-wing absorption.

A robust reconstruction of the intrinsic Lyman α flux may ultimately require a more sophisticated analysis than the one presented here. We have shown that there is some uncertainty in the Lyman α profile related to the C IV properties, and hence motivation to re-examine the claim of a damping wing. A conclusive analysis, however, may need to take into account the detailed properties of all available emission lines, and be verified through tests on lower redshift quasars with known Lyman α profiles.

5 CONCLUSIONS

Composites quasar spectra have been used in the past to study the IGM around ULAS J1120+0641 and hypothesize a large fraction of neutral gas or very metal poor gas. Those claims were based on ULAS J1120+0641's seemingly highly absorbed Lyman α emission (Mortlock et al. (2011) using the quasar composite technique from Hewett & Wild 2010, Simcoe et al. 2012 and Bolton et al. 2011). However, those authors acknowledge the difficulty of producing a composite fit to ULAS J1120+0641, due primarily to the rarity of suitable objects. As a result, composite fits have mismatched its C IV emission line by ∼600 km s^{-1} or more in blueshift. Mortlock et al. (2011) suggested that this mismatch might have an impact on the existence of a Lyman α damping wing.

We have tested the effect of this small C IV mismatch by selecting a sample of 111 SDSS DR7 quasars at $2.4 < z < 4$ that more closely match ULAS J1120+0641's C IV emission, and a second sample of 216 quasars whose C IV emission lines match ULAS J1120+0641's in EW but are offset bluewards by ∼600 km s^{-1} (∼3 Å in the rest frame). We find that among a population of quasars which match its C IV emission in EW and shape, but offset by ∼600 km s^{-1} from the correct C IV line systematic blueshift, ULAS J1120+0641 appears anomalous to a confidence of 97 per cent, in agreement with Mortlock et al. (2011) who find ULAS J1120+0641 to be a 2σ outlier from their composite fit. When compared to a population of lower redshift quasars which match its C IV line emission, however, ULAS J1120+0641's Lyman α flux does not appear to be anomalously weak.

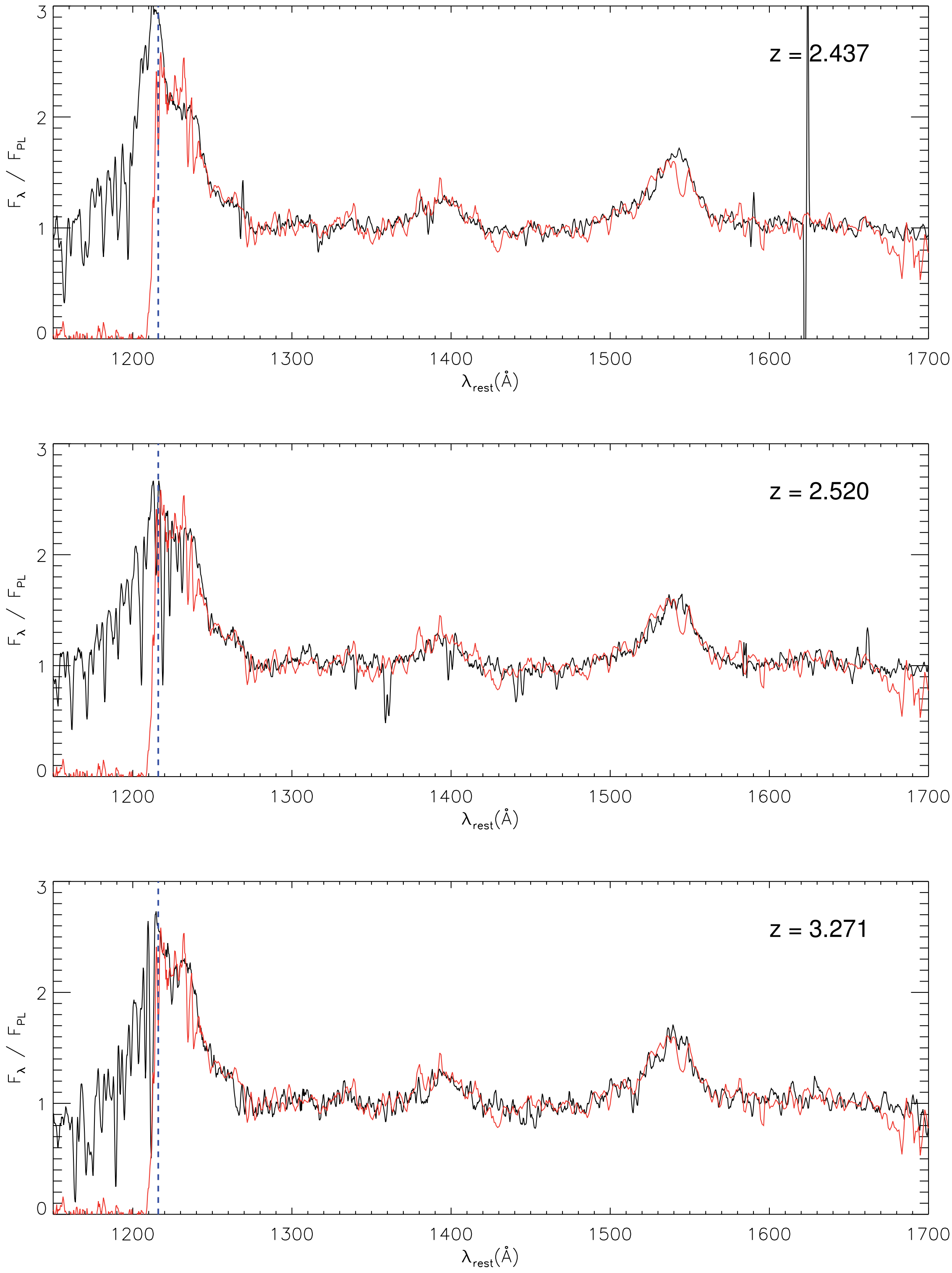

Figure 6. SDSS spectra of objects at lower redshifts which match J1120+0641's spectrum in C IV as well all the way to the onset of the Lyman α forest at 1216 Å, indicated by the blue dashed line. The GNIRS spectrum of ULAS J1120+0641, binned in bins of three, is overlaid in red. All spectra are normalized by a fitted power law. SDSS spectra are binned in bins of five. The C IV parameters of these objects are shown as green dots on Fig. 4.

In light of our results, we suggest that the shape of the Lyman α line in ULAS J1120+0641 is not obviously due to a damping wing. We note that the case for neutral gas in the vicinity of ULAS J1120+0641 depended on both the damping-wing absorption and the shortness of the proximity zone (Bolton et al. 2011). The latter could be due to an optically thick absorber near the quasar redshift, a point we will address in a future paper. Independent of the ULAS J1120+0641 constraints, however, there is evidence for a significantly neutral IGM at redshifts $z \geq 7$ from the evolution of the Lyman α emission fraction in galaxies (e.g. Caruana et al.

2012; Treu et al. 2013; Choudhury et al. 2014; Tilvi et al. 2014). Direct evidence from quasars would significantly strengthen this claim. Larger samples of quasars at $z \geq 7$, along with a more robust method to reconstruct their intrinsic Lyman α flux, are therefore of great interest for future reionization studies.

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