Evidence for Short $\sim 1$ Myr Lifetimes from the He $\text{ii}$ Proximity Zones of $z \sim 4$ Quasars

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ABSTRACT

The duration of quasar accretion episodes is a key quantity for distinguishing between models for the formation and growth of supermassive black holes, the evolution of quasars, and their potential feedback effects on their host galaxies. However, this critical timescale, often referred to as the quasar lifetime, is still uncertain by orders of magnitude ($t_Q \approx 0.01$ Myr $– 1$ Gyr). Absorption spectra of quasars exhibiting transmission in the He $\text{ii}$ Ly$\alpha$ forest provide a unique opportunity to make precise measurements of the quasar lifetime. Indeed, the size of a quasar’s He $\text{ii}$ proximity zone, the region near the quasar itself where its own radiation dramatically alters the ionization state of the surrounding intergalactic medium (IGM), depends sensitively on its lifetime for $t_Q \leq 30$ Myr, comparable to the expected e-folding time-scale for SMBH growth $t_e = 45$ Myr. In this study we compare the sizes of He $\text{ii}$ proximity zones in the Hubble Space Telescope (HST) spectra of six $z \approx 4$ quasars to theoretical models generated by post-processing cosmological hydrodynamical simulations with a 1D radiative transfer algorithm. We introduce a Bayesian statistical method to infer the lifetimes of individual quasars which allows us to fully marginalize over the unknown ionization state of He $\text{ii}$ in the surrounding IGM. We measure lifetimes $t_Q = 0.63^{+0.82}_{-0.40}$ Myr and $t_Q = 5.75^{+4.72}_{-2.74}$ Myr for two objects. For the other four quasars large redshift uncertainties undermine our sensitivity allowing us to only place upper or lower limits. However a joint analysis of these four systems yields a measurement of their average lifetime of $\langle t_Q \rangle = 1.17^{+1.77}_{-0.84}$ Myr. We discuss our short $\sim 1$ Myr inferred lifetimes in the context of other quasar lifetime constraints and the growth of SMBHs.

Key words: quasars: general — intergalactic medium — reionization

1 INTRODUCTION

Quasars are the most luminous non-transient sources of radiation in the Universe. It is believed that they played an important role in the evolution of cosmic structure on all scales, for instance dramatically changing the ionization and thermal state of the surrounding intergalactic medium (McQuinn et al. 2009; Compostella et al. 2013; Khrykin et al. 2016, 2017; Chardin et al. 2017; Davies et al. 2017; La Plante et al. 2017; D’Aloisio et al. 2017), but also possibly regulating star formation in galaxies (Springel et al. 2005; Hopkins et al. 2006). Many questions about the nature of quasars and their evolution remain unanswered. For example, the existence of SMBHs with masses $M_{\text{BH}} \approx 10^9 – 10^{10} M_\odot$ (Fan et al. 2001, 2004; Mortlock et al. 2011; Venemans et al. 2013; De Rosa et al. 2014; Wu et al. 2015; Bañados et al. 2018) already at $z \sim 6 - 7$ poses a challenge for current theories of SMBH formation, requiring very massive initial black hole seeds and accretion of matter on time-scales comparable to the Hubble time (Hopkins & Hernquist 2009; Volonteri 2010, 2012). Solving this puzzle is impossible without constraints on the characteristic time-scale over which accretion on to SMBHs occurs.

A holy grail would thus be a direct measurement of the lifetime $t_Q$ of quasars at high redshift, or more precisely the duration of their individual accretion episodes. This would shed light on triggering and feedback mechanisms (Springel et al. 2005; Hopkins et al. 2006), on how gas funnels to the centers of galaxies, and on the structure of the inner accretion disc (Goodman 2003; Hopkins & Quataert 2010). Unfortunately, the best currently available estimates on the time-scales governing quasar activity are uncertain by several orders of magnitude (see Martini 2004 for a review). For instance, studies of quasar demographics which attempt to model the quasar luminosity function and/or quasar clustering (Haiman & Hui 2001; Martini & Weinberg 2001) constrain the total integrated time that a galaxy hosts an active quasar, known as the quasar duty cycle $t_{dc}$. These studies often come to very different conclusions depending on the particular assumptions made in the modeling, but constraints

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are in the range \( t_{\Delta} \approx 1 \text{Myr} \sim 1 \text{Gyr} \) (Yu & Lu 2004; Adelberger & Steidel 2005; Croom et al. 2005; Shen et al. 2009; White et al. 2012; Conroy & White 2013; Cen 2015; La Plante & Trac 2016). In particular, the very strong clustering of quasars measured at \( z \approx 4 \) implies \( t_{\Delta} \sim 1 \text{Gyr} \) (Shen et al. 2007; White et al. 2008), much higher than estimates of this duty cycle at lower-\( z \), and seems to require an extremely tight relationship between the black hole mass \( M_{\text{BH}} \) and the halo mass \( M_{\text{halo}} \) (White et al. 2008). It is important to note that while these demographic studies constrain the quasar duty cycle \( t_{\Delta} \), they are insensitive to the duration of individual accretion episodes \( t_{Q} \), which theoretical models suggest could be much shorter (Ciotti & Ostriker 2001; Novak et al. 2011).

Previous studies employing a variety of techniques have found tentative evidence for short episodic quasar lifetimes \( t_{Q} \). For example, recent work by Schawinski et al. (2010, 2015) based on light travel time arguments in active galactic nuclei (AGN) host galaxies argues for quasar variability on time-scales of \( t_{Q} \approx 0.1 \) Myr. However, plausible alternative scenarios related to AGN obscuration could explain those observations without invoking short time-scale quasar variability, and furthermore the giant \( 500 \text{kpc} \) Ly\( \alpha \) nebulae discovered around \( z \approx 2 \) quasars (Cantalupo et al. 2014; Hennawi et al. 2015) implies quasar lifetimes of \( \gtrsim 1 \) Myr, at odds with these short inferred lifetimes. Oppenheimer et al. (2018) (see also Gonçalves et al. 2008) argued that the high incidence of strong high-ionization absorption lines in the circumgalactic medium of galaxies provides evidence for relic light echoes from an AGN, implying \( t_{Q} \approx 1 \) Myr, but the nature of these absorbers is a subject of intense debate and many models manage to explain them (Sterren et al. 2016, 2018; Mathews & Prochaska 2017; McQuinn & Werk 2018) without invoking a previously active AGN. Finally, the presence of high equivalent width Ly\( \alpha \) emitters (LAEs) near hyper-luminous quasars has been attributed to quasar-powered fluorescence and invoked to argue for quasar lifetimes of \( 1 \lesssim t_{Q} \lesssim 30 \) Myr (Trainor & Steidel 2013; Borissova et al. 2016). However, the expected boost due to the quasar illumination is inconsistent with the much brighter observed Ly\( \alpha \) luminosities of these LAEs, strongly suggesting that these sources are powered intrinsically and not by the nearby quasar (but see Adelberger et al. 2006). To summarize, all of the aforementioned methods are indirect and often involve model-dependent assumptions, such that plausible alternative scenarios can be invoked to explain the observations.

On the other hand, the ionization state of the IGM in quasar environments provides a powerful method to estimate quasar lifetimes. For example, using the observational survey data presented in Schmidt et al. (2017), Schmidt et al. (2018) carefully analyzed the He\( \text{II} \) Ly\( \alpha \) transverse proximity effect (TPE; Worseck & Wisotzki 2006; Jakobsen et al. 2003; Schmidt et al. 2017), which is the increased IGM He\( \text{II} \) Ly\( \alpha \) transmission in a background quasar sightline due to the enhancement of the radiation field from a foreground quasar. They found that the strength of the TPE signal exhibits a degeneracy between quasar lifetime and the solid angle of the UV emission (or equivalently the fraction of quasars that are obscured), and uncovered a possible bimodality in quasar emission properties whereby some quasars appear to be unobscured and relatively long lived (\( t_{Q} \gtrsim 10 \) Myr), whereas others are either younger (\( t_{Q} \lesssim 10 \) Myr) or highly obscured.

This degeneracy with quasar obscuration can be removed if one instead considers the line-of-sight (LOS) proximity effect, since the background quasar illuminates the IGM along our sightline towards Earth by construction. Indeed, the LOS proximity effect in the H\( \text{I} \) Ly\( \alpha \) forest at \( z \approx 2 \sim 4 \) (Carswell et al. 1982; Bajtlik et al. 1988) has been used to constrain \( t_{Q} \), but it provides only weak lower limits on \( t_{Q} \gtrsim 0.01 \) Myr (Dall’Aglio et al. 2008). This limit results from the fact that in order to produce a detectable LOS proximity effect the quasar must shine longer than the time it takes the IGM to attain ionization equilibrium with the enhanced quasar radiation, the so-called equilibration time-scale \( t_{eq} \sim t_{\text{HI}}^{-1} \). Given the measurements of the UV H\( \text{I} \) background photoionization rate \( \Gamma_{\text{HI}} \approx 10^{-12} \text{cm}^{-3} \) (Becker et al. 2013) at \( z \approx 3 \sim 5 \), the H\( \alpha \) proximity effect is, in principle, detectable, provided that \( t_{Q} \gtrsim 0.01 \) Myr. This argument provides the basis for the recent discovery of a population of very young quasars \( t_{Q} \lesssim 0.01 \sim 0.1 \) Myr at \( z \approx 6 \) (Eilers et al. 2017, 2018) as inferred from small sizes of their LOS proximity zones. It remains unclear whether a similar population of young quasars exists at lower redshift. It could be that they have only been uncovered at \( z \approx 6 \) because the much higher Ly\( \alpha \) optical depth of the surrounding IGM makes their small proximity zones particularly conspicuous. In addition, a more precise constraint on lifetime can be obtained if one combines the analysis of high-\( z \) H\( \alpha \) proximity zones with the study of damping wing signatures in the quasar spectra (Davies et al. 2018). This approach, applied to the spectra of two most distant \( z \approx 7 \) quasars, provides evidence for the lifetime \( t_{Q} \lesssim 10 \) Myr (Davies et al. in prep).

Khrykin et al. (2016) showed that the analogous LOS He\( \text{II} \) Ly\( \alpha \) proximity effect (Hogan et al. 1997; Anderson et al. 1999; Zheng et al. 2015) at \( z \approx 3 \sim 4 \) is sensitive to quasar lifetimes on longer and more interesting time-scales of up to \( t_{Q} \approx 30 \) Myr, comparable to the Salpeter or e-folding (Salpeter 1964) time-scale for SMBH growth \( t_{\ast} \approx 45 \) Myr. This arises from the fact that the equilibration time-scale for He\( \text{II} \) at these redshifts is three orders of magnitude longer owing to the much lower He\( \text{II} \) photoionization rate \( t_{eq} \approx \Gamma_{\text{HeII}}^{-1} \approx 30 \) Myr (Khrykin et al. 2016). Fortunately, significant observational effort over the last several years has resulted in the discovery of large numbers of new \( z \approx 3 \sim 4 \) quasar sightlines which are transparent at He\( \text{II} \) redshifts (Worseck et al. 2011; Syphers et al. 2012; Worseck et al. 2016). But to date these He\( \text{II} \) proximity zones have not yielded convincing quantitative constraints on the time-scales governing quasar emission (but see Zheng et al. 2015; Syphers & Shull 2014).

In this work we compare the proximity zones of six \( z \approx 3.7 \sim 3.9 \) quasars from Worseck et al. (2018) to theoretical models and obtain the first robust quantitative constraints on quasar lifetime from the He\( \text{II} \) Ly\( \alpha \) LOS proximity effect. Our modeling builds on Khrykin et al. (2016), where a custom 1D radiative transfer algorithm was used to post-process outputs from a cosmological hydrodynamical simulation, which takes into account the radiation from the quasar and the metagalactic ionizing background which sets the ionization state of the ambient IGM. Whereas previous analyses of He\( \text{II} \) proximity zones made specific assumptions about the ionization state of the ambient IGM, whereas previous analyses of He\( \text{II} \) proximity zones made specific assumptions about the ionization state of the ambient IGM. Whereas previous analyses of He\( \text{II} \) proximity zones made specific assumptions about the ionization state of the ambient IGM.

This paper is organized as follows. In Section 2 we summarize the observations and the parameters of the quasars in our dataset. We outline our numerical model in Section 3. In Section 4 we describe our new Bayesian method for measuring the quasar lifetime and He\( \text{II} \) fraction, and present the results of our inference in Section 5. We discuss our findings in Section 6, and conclude in Section 7. 

Throughout this work we assume a flat \( \Lambda \)CDM cosmology with dimensionless Hubble constant \( h = 0.7, \Omega_{\text{m}} = 0.27, \Omega_{\Lambda} = 0.046 \)
Positions, resulting in somewhat different spectral resolutions the HST are taken from Worseck et al. (2018), where a detailed description board the HST. Table 1 summarizes their key properties. Six of them with the Cosmic Origins Spectrograph (COS; Green et al. 2012) on We use a sample of 7 2 DATA SAMPLE explicitly stated otherwise.

### Table 1. Main parameters of 7 quasars used in this study. From left to right the columns show: quasar name, quasar position, COS spectral resolution at 1450Å, signal-to-noise ratio per 0.24Å pixel near He II Ly α, quasar redshift, redshift uncertainty, spectroscopic line that was used to measure the redshift, i-band magnitude, absolute magnitude at 1450Å, H i and He ii total photon production rates Q_{1R} and Q_{2R}, measured size of the proximity zone R_{pz} with corresponding 1σ redshift uncertainty, and the inferred lifetime t_{q,1}.

| Quasar     | R.A. (degree) | Decl. (degree) | R | S/N | z | Δν | z line | i-mag | M_{1450} | log_{10}Q_{1R} | log_{10}Q_{2R} | R_{pz} z + σ( R_{pz} ) | log_{10}[t_{q,1}/Myr] |
|------------|---------------|----------------|---|-----|---|----|--------|------|----------|-----------------|----------------|---------------------|---------------------|
| HE2QS J2354–1920 | 22 50 00 00 | –14.17521 | 2000 | 4 | 3.700 | 656 | C iv | 18.11 | –27.64 | 57.56 | 56.66 | 1.94 ± 1.72 | < 0.31 |
| HE2QS J1630+0035 | 16 30 56 34 | +04.35594 | 2000 | 4 | 3.810 | 400 | H β | 17.51 | –28.37 | 57.82 | 56.92 | 8.43 ± 1.02 | 0.76 ± 0.26 |
| HE2QS J1634+0045 | 16 42 28 01 | +04.58588 | 2000 | 3 | 3.817 | 656 | C iv | 19.45 | –26.34 | 57.05 | 56.14 | 2.72 ± 1.66 | < 1.19 |
| HE2QS J2354–2033 | 23 54 25 00 | –20.33207 | 2000 | 3 | 3.774 | 656 | C iv | 18.90 | –26.88 | 57.27 | 56.37 | −3.65 ± 1.68 | — |
| SDSS J1711+0605 | 17 11 33 41 | +60.52403 | 2000 | 4 | 3.835 | 656 | C iv | 19.34 | –26.49 | 57.10 | 56.19 | 2.97 ± 1.65 | < 1.25 |
| SDSS J2319+5203 | 23 19 12 40 | +52.02001 | 2000 | 2 | 3.916 | 450 | H β | 17.81 | –28.02 | 57.73 | 56.82 | 3.62 ± 0.98 | −0.20±0.30 |

σ_{q,1} = 0.8 and n_{p,1} = 0.96 (Larson et al. 2011), and helium mass fraction Y_{He} = 0.24. All distances are quoted in proper Mpc unless explicitly stated otherwise.

### 2 DATA SAMPLE

We use a sample of 7 z ≥ 3.7 He ii-transparent quasars observed with the Cosmic Origins Spectrograph (COS; Green et al. 2012) on board the HST. Table 1 summarizes their key properties. Six of them are taken from Worseck et al. (2018), where a detailed description of the observations and the data reduction are presented. Here we summarize the most relevant details. The spectra were taken with the HST/COS G140L grating at different COS Detector Lifetime Positions, resulting in somewhat different spectral resolutions R = λ/Δλ = 2,000–2,700 at the wavelengths of interest near He ii Ly α (λ = 1450 Å). The spectra have been rebinned to 0.24 Å pixel^{-1} yielding a sampling of 2–3 pixels per resolution element, and the signal-to-noise ratio (S/N) per pixel near He ii Ly α varies from two to four.

To this sample we add the quasar HE2QS J2354–2033 that had been discovered in our dedicated ground-based survey for UV-bright high-redshift quasars (Worseck et al. 2018). HST/COS G140L follow-up spectroscopy was obtained in Program 14809 (PI Worseck) on 30 October 2016 at COS Lifetime Position 3, yielding a spectral resolution R = 2,300 at 1450 Å. A single four-orbit visit (total exposure time 11,131 s) yielded a S/N of 3 per 0.24 Å pixel in the quasar continuum near He ii Ly α. The individual exposures were reduced with the CALCOS pipeline v2.21, and then post-processed with custom software for accurate background estimation and co-addition in the Poisson limit, as described in Worseck et al. (2016, 2018). Custom COS detector pulse height screening was employed to minimize the dark current while including almost all source flux. We determined a science pulse height range 2–12 from the strong geocoronal H i Ly α line. For dark current subtraction in the spectral trace we used a sample of COS dark monitoring data taken within three months centred on the date of the science observations as in Worseck et al. (2016, 2018).

The spectra were corrected for Galactic extinction adopting the respective selective extinction E(B-V) from Schlegel et al. (1998) and the Cardelli et al. (1989) extinction curve assuming the Galactic average ratio between total V band extinction and selective extinction R_{V'} = 3.1. The extinction-corrected spectra were normalized with power-law continua redward of He ii Ly α, accounting for low-redshift H i Lyman limit breaks Worseck et al. 2016, 2018.

Only one quasar in the sample (SDSS J1137+6237) shows signs of He ii Lyα emission that we do not incorporate in the continuum model. Its neglect, as well as other (percent-level) continuum errors do not affect our measurements of the proximity zone size.

In order to estimate the size of the proximity zone (R_{pz}) for each quasar spectra we follow previous conventions used in the studies of H i proximity zones (Fan et al. 2006; Bolton & Haehnelt 007a; Lidz et al. 2007; Carrill et al. 2010; Eilers et al. 2017) and define R_{pz} to be the location in the spectrum where the smoothed H i transmission profile drops below 10 per cent for the first time. Fan et al. (2006) used a Gaussian filter with FWHM = 20 Å (in the observed frame) to smooth the spectra. This smoothing scale corresponds to a velocity interval Δv ~ 700 km s^{-1} or a distance interval ΔR = 0.97 Rpz at z ~ 6. We adopt the same smoothing scale ΔR = 0.97 Rpz per Mpc at redshifts of the quasars in the data sample, and apply a Gaussian filter to all H i Lyα transmission profiles. Because the smoothing length is larger than the spectral resolution and includes several pixels, the measured proximity zone size does only weakly depend on the S/N of the spectra, and we do not include these effects into our numerical calculations below. Fig. 1 illustrates the He ii transmission profiles of each quasar in our sample. The smoothed H i transmission is indicated by the black lines. The magenta error bars indicate the corresponding redshift uncertainty of each quasar.

The dominant source of uncertainty in our proximity zone measurements results from quasar redshift errors. It is well known that the primary broad rest-frame UV/optical emission lines that are accessible in the optical/near-IR for z > 3.5 quasars have line centres which can differ from systemic by as much as ~ 3000 km s^{-1} due to outflowing/inflowing material in the so-called broad line regions of quasars (Gaskell 1982; Tytler & Fan 1992; Vanden Berk et al. 2001; Richards et al. 2002; Shen et al. 2016). To robustly determine systemic redshifts and associated errors for the quasars in our sample, we adopt an approach similar to that described in Shen et al. (2016). The idea is to use a training sample of quasars for which the broad lines in question are present, as well as other features which are known to be good tracers of the systemic frame. For cases where the only strong broad far-UV lines like C iv λ1549 are available, as is the case at z > 3.5 if only optical spectra are
Figure 1. He II transmission spectra of 7 $z \approx 4$ quasars in our data sample (see Table 1). The blue binned lines show the HST/COS spectra (0.24 Å/pixel), whilst the black lines show the 0.97 Mpc-smoothed He II transmission, respectively. The magenta error bar illustrates the redshift uncertainty of the corresponding quasar. The values of measured proximity zone sizes are indicated by the red squares, where the smoothed transmission crosses the 10 per cent threshold (red horizontal lines).

SDSSJ1319+5202
$R_{\text{pz}} = 3.61\pm0.98$ pMpc
$z = 3.916\pm0.007$

SDSSJ1711+6052
$R_{\text{pz}} = 2.97\pm1.65$ pMpc
$z = 3.835\pm0.011$

HE2QSJ2354-2033
$R_{\text{pz}} = -3.65\pm1.68$ pMpc
$z = 3.774\pm0.01$

SDSSJ1614+4859
$R_{\text{pz}} = 2.72\pm1.66$ pMpc
$z = 3.817\pm0.011$

HE2QSJ1630+0435
$R_{\text{pz}} = 8.43\pm1.02$ pMpc
$z = 3.81\pm0.006$

SDSSJ1137+6237
$R_{\text{pz}} = 4.92\pm1.68$ pMpc
$z = 3.788\pm0.01$

HE2QSJ2311-1417
$R_{\text{pz}} = 1.94\pm1.72$ pMpc
$z = 3.7\pm0.01$
available, then one can similarly use a training set to calibrate the relationship between C iv redshifts and those determined from the lower ionization (but still broad) Mg ii λ2798 emission line, which is known to be an excellent tracer of the systemic frame (Shen et al. 2016).

Of the seven quasars in our sample, two objects SDSS J1319+5202 and HE2Q5 J1630+0435 have high-quality near-IR spectra which enable a redshift measurement from the rest-frame optical H β lines which are redshifted into the K-band (Worseck et al in prep.). For the other five quasars in our sample which lack high-quality near-IR spectra, we determine redshifts from the C iv emission line, which is the strongest line detected redward of H Ly α. The broad H β and C iv emission lines were centred using the algorithm described in Hennawi et al. (2006), which is robust against spectral noise, line asymmetries, and associated absorption features (which can affect C iv). For the two objects with H β redshifts, we transformed into the systemic frame using the average blueshift of $-109 \text{ km s}^{-1}$ and assigned them a redshift error of 400 km s$^{-1}$, following the values derived by Shen et al. (2016). For the other five with C iv the procedure is slightly more complicated. It is well known that the blueshift of the C iv line is luminosity dependent, which is known as the Baldwin effect (Baldwin 1977). Thus to obtain systemic redshifts from C iv we follow Shen et al. (2016) and use a training set to fit for the luminosity dependent blueshift between C iv and Mg ii redshifts. To briefly summarize how we calibrated the luminosity dependent blueshift, we used a sample of 2504 quasars from the Baryon Oscillation Spectroscopic Survey (BOSS; Pâris et al. 2018) with sufficient wavelength coverage and S/N ratio that redshifts from both C iv and Mg ii can be obtained. These quasars have monochromatic luminosities at 1450Å in the range $\log L_{1450} \approx 43.5 - 47$, where $\log L_{1450}$ is determined from the $i$-band apparent magnitudes of the quasars and a composite quasar spectrum following the approach described in Appendix A of Hennawi et al. (2006). To quantify the luminosity dependent velocity shift we bin these data in luminosity with a bin size of $\Delta \log L = 0.25$ and compute the mean shift in each bin after sigma clipping outliers. The error on the mean is determined from the standard deviation and divided by $\sqrt{N}$, where $N$ is the number of points considered, i.e. those that survived sigma clipping. Following Shen et al. (2016) we fit a simple linear relation for the dependence of these velocity shifts on $\log L_{1450}$

$$v = a + b \log L_{1450} - \log L_{1450,0}$$

where $\log L_{1450,0} = 45$. This procedure yields $a = -192.4 \text{ km s}^{-1}$ and $b = -599.6 \text{ km s}^{-1}$, which is in reasonable agreement with the independent result obtained by Shen et al. (2016) for a distinct training set, and different line centering algorithms. Using this fit, we then transform every C iv redshift in this training set into the systemic frame (here defined by the Mg ii redshift). An error on this procedure can be estimated by considering the distribution of these estimated Mg ii redshifts about their true values. We find that this distribution is well described by a Gaussian with a mean $-79 \text{ km s}^{-1}$ and standard deviation 656 km s$^{-1}$, and we use the latter as the error on our C iv redshifts. Note that for these C iv redshifts, we simply assume that Mg ii frame perfectly traces systemic. Neglecting the small differences between the Mg ii frame is a valid assumption given the results from Shen et al. (2016), who found that the distribution of Mg ii about systemic (defined by the [O ii] emission line) is well described by a Gaussian with mean $-20 \text{ km s}^{-1}$ and standard deviation 200 km s$^{-1}$ — both of which are much smaller than our inferred error budget of 656 km s$^{-1}$ arising from the imperfect correlation between C iv-Mg ii and redshifts.

Unfortunately, in case of quasar HE2Q5 J2354–2033, its redshift appears to be significantly underestimated. From the extent of the He ii proximity zone we conclude that the C iv emission line of this quasar, that was used to measure the systemic redshift, has a very large blueshift. This is clearly seen in Fig. 1, where the resulting He ii proximity zone has a hugely negative size ($R_p = -3.65 \pm 1.68 \text{ Mpc}$). Regrettably, there are no other strong lines in the spectrum of HE2Q5 J2354–2033 redward of H Ly α that can be used to accurately determine the redshift of this quasar. Therefore, we exclude the quasar HE2Q5 J2354–2033 from the subsequent analysis after the initial inspection of the He ii proximity zone, because it cannot provide reasonable constraint on the lifetime.

The redshifts, associated redshift errors, and the emission line used to infer the redshift are given in Table 1. The full details of our procedure, as well as information about the near-IR spectra and the data used for each quasar redshift are provided in Worseck et al. (2018).

3 MODELING HE ii LY α PROXIMITY ZONES

Our numerical model consists of hydrodynamical simulations and a 1D post-processing radiative transfer algorithm for transport of the ionizing radiation from the quasar through the IGM. In this section we provide the most important details of our model and refer the reader to the full description given in Khrykin et al. (2016, 2017).

We use the Gadget-3 code (Springel 2005) with simulation box size of $25h^{-1} \text{ Mpc}$ on a side, containing $2 \times 512^3$ particles. Using periodic boundary conditions we extract 1000 density, velocity, and temperature fields (skewers) drawn in random directions around the most massive haloes ($M > 5 \times 10^{11} M_\odot$) in the outputs of hydrodynamical simulations at $z = 3.7$ and $z = 3.9$. The resulting skewers have a total length of 160 comoving Mpc with a pixel scale $\delta r = 0.01 \text{ comoving Mpc}$ ($\delta v = 1.0 \text{ km s}^{-1}$).

Extracted skewers are used in our 1D post-processing radiative transfer algorithm based on the C2-Ray code (Mellema et al. 2006), which calculates the evolution of the abundances of $e^-$, $H_i$, He ii, and the gas temperature (Khrykin et al. 2016, 2017). Assuming there is no evolution of cosmic structure between the redshifts of the simulation outputs and that of the corresponding quasars, we simply rescale the gas density of the skewers by a factor $(1 + z)^3$ to account for cosmological density evolution, where $z$ is the redshift of the quasar that we are simulating (see Table 1).

There are several important parameters which govern quasar He ii proximity zones: the quasar systemic redshift, the photon production rates $Q_{1Ry}$ and $Q_{4Ry}$ above 1Ry and 4Ry, respectively, the quasar lifetime $t_Q$, and the He ii ionizing background, which sets the value of the initial He ii fraction $x_{HeII0}$, which prevailed in the IGM before the quasar turned on (Khrykin et al. 2016, 2017). For each quasar in our data sample we create a custom set of radiative transfer models based on these parameters. Using their observed $i$-band magnitudes, we compute $Q_{1Ry}$ and $Q_{4Ry}$ for each quasar in our sample (see Table 1) according to the procedure outlined in Hennawi et al. (2006, see also Section 6). These values, together with the systemic redshift $z$ are fixed for all radiative transfer models of each individual quasar in our data sample. On the other hand, we

\footnote{In what follows we quote the values of initial He ii fraction that correspond to the adopted values of the He ii background in the radiative transfer simulations.}
whereas the initial He\textsubscript{II} values are indicated by the black arrows. We smooth our simulated He\textsubscript{II} following the same procedure applied to the observational data, by red squares) are indicated by the black arrows.

explore different combinations of the parameters \( t_{Q, \text{HeII}_0} \). We consider logarithmically spaced quasar lifetime values in the range \( \log_{10} (t_Q/\text{Myr}) = [-2.0, 2.0] \), with \( \Delta \log_{10} (t_Q/\text{Myr}) = 0.125 \), whereas the initial He\textsubscript{II} fraction can have one of the following values: \( \text{HeII}_0 = [0.05, 0.10, 0.20, 0.30, 0.50, 0.60, 0.70, 0.90, 1.00] \). This results in a grid of 297 radiative transfer models, with 1000 He\textsubscript{II} Ly\textalpha transmission spectra per model, for each quasar in our data sample.

4 ESTIMATING THE QUASAR LIFETIME AND INITIAL HE\textsubscript{II} FRACTION

4.1 Mock He\textsubscript{II} Spectra and the Size of the Proximity Zone

Following the same procedure applied to the observational data, we smooth our simulated He\textsubscript{II} Ly\textalpha transmission spectra in this way are shown by the black curves in Fig. 2, whereas the blue curves show the original full-resolution mock spectra that results from our modeling procedure. The proximity zone sizes are marked by the red squares. It is apparent from the left side panels of Fig. 2 that, as expected, the size of the proximity zone increases for longer quasar lifetimes. This dependence of the proximity zone size on quasar lifetime exists because the IGM responds to the changes in the radiation field and attains a new ionization equilibrium state on a finite equilibration time-scale, which is \( t_{eq} \approx 1/\Delta t_{\text{bkg}} \approx 30 \) Myr for He\textsubscript{II} at \( z \approx 3 – 4 \) (Khrykin et al. 2016). The left panel of Fig. 3 illustrates the dependence of \( R_{pz} \) on quasar lifetime determined from our mock spectra with different lifetimes. It is apparent that for short quasar lifetimes (\( t_Q \approx t_{eq} \)) the median proximity zone size \( R_{pz} \) grows with lifetime, until \( t_Q \) becomes larger than the equilibration time (\( t_Q \approx t_{eq} \), at which point the median \( R_{pz} \) saturates and stops growing (Khrykin et al. 2016).

A much weaker increasing trend can be seen in the right panels of Fig. 2 where the \( R_{pz} \) is larger for higher initial He\textsubscript{II} fraction. This trend may seem counter-intuitive upon examination of the full-resolution transmission profiles (blue curves), which exhibit more transmission at larger distances from the quasar for lower values of initial He\textsubscript{II} fraction. This is because the shape of the transmission profile depends on both the initial He\textsubscript{II} fraction, which is set by the ionizing background, as well as the amount of photoelectric heating of the IGM resulting from the reionization of He\textsubscript{II}, which is known as the thermal proximity effect (Khrykin et al. 2017, see also Bolton et al. 2009; Meiksin et al. 2010). The overall increase in transmission at larger radii from the quasar in models with low \( \text{HeII}_0 \) is caused by the higher He\textsubscript{II} background as compared to models with \( \text{HeII}_0 > 0.50 \). Khrykin et al. (2016) showed that the effect of He\textsubscript{II} background, which sets the value of the initial He\textsubscript{II} fraction, on He\textsubscript{II} proximity zone becomes prominent at distances where the quasar...
photoionization rate $\Gamma_{\text{HeII}}^{QSO}$ is no longer the dominant contribution to the total photoionization rate, i.e., $\Gamma_{\text{HeII}}^{QSO} \lesssim \Gamma_{\text{HeII}}^{bg}$. However, the standard definition of the proximity zone size that we use, which is when the smoothed transmission crosses 10 per cent, is insensitive to the information about $\Gamma_{\text{HeII}}^{QSO}$ encoded in the He~\textsc{ii} transmission at the outskirts of the proximity zones. This is because at larger distances where $\Gamma_{\text{HeII}}^{QSO}$ becomes comparable to the background the transmission is much lower than 10 per cent, which is visible in the right panels of Fig. 2 (a similar argument explains why the H~\textsc{i} Ly$\alpha$ proximity zones of $z \sim 6$ quasars are not good probes of $\xi_{\text{HI}}$ and reionization (Eilers et al. 2017)). On the other hand, the photoionization of He~\textsc{ii} by the quasar causes significant heating of the IGM gas. The more singly ionized helium present in the surrounding IGM, the more photoelectric heating results from the absorption of hard photons. Because of the $\tau_{\text{HeII}} \propto T^{-0.7}$ temperature dependence of the He~\textsc{ii} Ly$\alpha$ optical depth, this heating boosts the transmission in the proximity zone for higher values of $x_{\text{HeII}}$ (Khrykin et al. 2017). Therefore, the smoothed transmission profiles cross the 10 per cent threshold at larger radii in case of higher $x_{\text{HeII}}$ values.

The competition between the increased transmission in the ambient IGM for small $x_{\text{HeII}}$, the 10 per cent transmission threshold being too high to be probe $\Gamma_{\text{HeII}}^{bg}$, and the increased transmission due to the thermal proximity effect for higher $x_{\text{HeII}}$ results in an overall weak dependence of proximity zone size with initial He~\textsc{ii} fraction, illustrated in the right panel of Fig. 3.

### 4.2 Distribution of the Proximity Zone Sizes

In general, density fluctuations in the IGM give rise to a broad distribution of proximity zone sizes $R_{\text{pz}}$ for a given set of model parameters (Khrykin et al. 2016), as illustrated in Fig. 3. Furthermore, the uncertainty in quasar redshifts also adds a significant amount of scatter. This is apparent from Table 1 where it is seen (second to last column) that our largest redshift errors, which are those derived from the C iv emission line, result in an uncertainty $\sigma(R_{\text{pz}}) \approx 1.7$ Mpc, comparable to the smallest measured proximity zone sizes. Notwithstanding these uncertainties, a comparison of the $R_{\text{pz}}$ distributions from our radiative transfer models to our data sample can still yield constraints on the quasar lifetime. This is readily apparent from inspection of Fig. 4, where we show the observed distribution of $R_{\text{pz}}$ along with the predicted distributions from our simulations for different combinations of model parameters $t_0$ and $x_{\text{HeII}}$. Similar to Fig. 2, the left panel of Fig. 4 shows the distribution of $R_{\text{pz}}$ for models with a fixed initial He~\textsc{ii} fraction ($x_{\text{HeII}} = 1.00$), and three different values of quasar lifetime whereas the right panel shows results at fixed quasar lifetime $\log_{10}(t_0/\text{Myr}) = 2.00$ and three different values of $x_{\text{HeII}}$. Each model histogram of simulated He~\textsc{ii} proximity zone sizes is derived from 600 mock $R_{\text{pz}}$ measurements - where we take 100 $R_{\text{pz}}$ from the model of each of the six quasars for the corresponding $\log_{10}(t_0/\text{Myr})$ and $x_{\text{HeII}}$ values. These model histograms are then normalized to six, which is the total number of quasars in our data sample. We incorporate redshift errors into our simulated distributions of $R_{\text{pz}}$ using the uncertainties on $\sigma(R_{\text{pz}})$ reported in Table 1. Specifically, we randomly draw a Gaussian distributed redshift error using the $\sigma(R_{\text{pz}})$ specific to each quasar and add these to the 100 simulated $R_{\text{pz}}$ values for each quasar and each combination of model parameters.

Inspection of the left panel of Fig. 4 already reveals that lifetimes around $t_0 \approx 1$ Myr appear to be preferred by the data. Whereas the right panel clearly indicates the high degree of overlap between the simulated histograms for different values of $x_{\text{HeII}}$. This overlap is a direct result of the weak dependence of $R_{\text{pz}}$ on initial He~\textsc{ii} fraction discussed in the previous section (see Fig. 3). This weak sensitivity combined with redshift uncertainties suggests it will be challenging to infer the $x_{\text{HeII}}$ for these quasars. We come back to this question in Section 5.

### 4.3 Bayesian Inference of Model Parameters

In order to estimate the lifetime and He~\textsc{ii} fraction for each quasar in our data sample we introduce a Bayesian likelihood for the observed proximity zone size $R_{\text{pz}}$ given these model parameters $x_{\text{HeII}}$, $t_0$, $\xi_{\text{HI}}$, $Q_{\text{cr},QSO}$, $\dot{Q}_{\text{cr},QSO}$, $\dot{Q}_{\text{cr},\text{QSO}}$, $Q_{\text{cr},\text{QSO}}$.

$$
\mathcal{L}(R_{\text{pz}}|t_0, x_{\text{HeII}}) = p(R_{\text{pz}}|t_0, x_{\text{HeII}}),
$$

where $p(R_{\text{pz}}|t_0, x_{\text{HeII}})$ is the probability density function (PDF) for $R_{\text{pz}}$ determined from our radiative transfer simulations for a given value of $t_0$ and $x_{\text{HeII}}$ (we omit $z, Q_{\text{cr},\text{QSO}}, Q_{\text{cr},\text{QSO}}$ in the notation for simplicity because these parameters are fixed for all models of any given quasar). Note that given the finite number of skews used in each model, $p(R_{\text{pz}}|t_0, x_{\text{HeII}})$ must be estimated from a discrete number of samples. To this end we use kernel density estimation.
As stated previously, redshift uncertainty constitutes a significant source of error, which would alter the outcome of the parameter inference if neglected. We therefore model the impact of these redshift uncertainties on the \( R_{pz} \) PDF by adding random Gaussian distributed redshift errors with standard deviation \( \sigma(R_{pz}) \) (see Table 1) to the simulated \( R_{pz} \) of each quasar, and perform the KDE on these noisy values. The results are illustrated in Fig. 5, where \( R_{pz} \) distributions with redshift uncertainty (\( \sigma(R_{pz}) = 1.72 \) pMpc for HE2QS J2311–1417, see Table 1) included are shown by green histograms, and the corresponding KDEs are illustrated by the blue lines. It is clear that incorporating redshift uncertainties into our \( R_{pz} \) distributions makes them broader and reduces the discriminative power of each individual proximity zone size measurement.

In order to calculate the likelihood of the data for any combination of model parameters, we can then simply evaluate the corresponding KDE PDF at the observed value of \( R_{pz} \) (see Table 1) for the quasar in question. This procedure results in 297 determinations of the likelihood at each location \( \{t_Q, x_{HeII,0}\} \) on our model grid for each quasar. We use bivariate spline interpolation to compute
Quasar Lifetimes at $z \approx 4$

5 RESULTS

Given the likelihood of our data given the model parameters in equation (2), and our interpolation procedure which allows us to evaluate this likelihood at any point in our parameter space $\{t_Q, x_{\text{HeII},0}\}$, we now proceed to sample this likelihood with MCMC to determine the posterior distribution of the model parameters for each quasar in the data sample. To this end we use the publicly available Python MCMC software emcee Foreman-Mackey et al. (2013), which implements an affine invariant MCMC ensemble sampling algorithm (Goodman & Weare 2010). The results of the MCMC sampling of the posterior distribution of each quasar in our data sample are shown in Fig. 6, where the contours illustrate the 95 (blue) and 68 per cent (red) confidence intervals, respectively. Marginalized posterior probability distributions for each parameter $\log_{10}(t_Q/\text{Myr})$ and $x_{\text{HeII},0}$ are also shown by the histograms. There are several noticeable results and trends that we now discuss.

5.1 Constraints on the Initial He II Fraction

We begin with the constraints on the initial He II fraction. As was previously stated in Section 4.2, the large degree of overlap between the model $R_{pz}$ distributions for different values of $x_{\text{HeII},0}$ and fixed $t_Q$ (see Fig. 4), which ultimately results from the very weak dependence of $R_{pz}$ on $x_{\text{HeII},0}$ shown in Fig. 3, suggests that it would...
be difficult to infer $x_{\text{HeII}}$0 with the current dataset. This is indeed the case – the broad flat posterior distributions for $x_{\text{HeII}}$0 in Fig. 6, which hardly differ from our assumed flat prior, indicate that the data is not very informative and the initial He n fraction in the ambient IGM surrounding our seven quasars is virtually unconstrained.

5.2 Constraints on the Quasar Lifetime

Fig. 7 shows the one dimensional posterior probability distributions for all seven quasars in our sample, marginalized over the initial He n fraction. It is clear upon inspection of these posterior that in some cases we are able to measure the quasar lifetime, whereas in others we can only set upper limits. Clearly this distinction depends upon the strength of the peak in the posterior probability. In order to distinguish between measurements and limits, we use the following criterion. If the maximum value of the marginalized posterior probability distribution is at least four times larger than the larger of the two posterior probability values at the edges of the $\log Q$ ($Q_{\text{Myr}}$) parameter grid, then we classify it as a measurement. In this case we quote the 95th percentile of the posterior distribution as the measured value, whereas the 16th and 84th percentiles are quoted as our uncertainties. On the other hand, for the flatter posterior probability distributions which do not satisfy the above criteria, we report an upper limit on the quasar lifetime. We choose to quote the 95th percentile value as our upper limit (effectively 2σ) on the lifetime.

One issue with the upper limits as we define them is that they clearly depend on the range of simulated $\log Q$ ($Q_{\text{Myr}}$) values, i.e., on our choice of a flat logarithmic prior on the quasar lifetime extending from $\log Q = -2.0$ to $\log Q = 2.0$. However, as was discussed in Section 4.3, the lower limit of our prior is physically motivated observations of the Hα LOS proximity effect. The upper limit of our prior is determined by limitations of our modeling procedure, but we see that the proximity zones are all so small that the resulting posteriors are all very small at $\log Q = 2.0$, and thus it does not influence our results.

The results of our lifetime inference for all quasars in our data sample are summarized in Table 1, which we discuss further in what follows.

5.2.1 SDSS J1319+5202

The red histogram in Fig. 7 illustrates the marginalized lifetime posterior probability distribution for the quasar SDSS J1319+5202. We infer the lifetime of $\log Q = -2.0^{+0.36}_{-0.45}$, indicating that this quasar is relatively young. It is also clear from the shape of the posterior that for this case of highly constraining data we are totally insensitive to our choice of priors. The reason we are able to constrain $Q_0$ so tightly for SDSS J1319+5202 is that it is the second most luminous object in our sample, which also has the smallest redshift uncertainty $\sigma(Q_{\text{eq}})$ = 0.98 Mpc as inferred from its Hβ emission line redshift (see Table 1).

Proximity zone sizes $Q_{\text{eq}}$ increase with luminosity (Khrykin et al. 2016), implying that the relative error on $Q_{\text{eq}}$ should be smallest for the brightest sources. This appears to be reflected in SDSS J1319+5202 which has the third largest proximity zone size of $Q_{\text{eq}} = 3.62 \pm 0.98$ Mpc. In contrast with the green histograms (blue curves) in Fig. 5 for HE2QS J2311−1417 which has a 90% relative error on $Q_{\text{eq}}$, the 27% relative error on $Q_{\text{eq}}$ for SDSS J1319+5202 implies its $Q_{\text{eq}}$ PDFs are significantly less broadened by the redshift uncertainty. As a result, the likelihood values, obtained by evaluating the respective KDE (see Section 4.3), are less similar for different $Q_0$ models, resulting in higher lifetime precision.

5.2.2 HE2QS J1630+0435

It is apparent from the green histogram in Fig. 7 that the best lifetime constraint we obtain is for the most luminous quasar in the sample HE2QS J1630+0435, which has $Q_{\text{eq}} = 8.43 \pm 1.02$ Mpc. From this distribution we deduce the lifetime to be $\log Q = 2.0^{+0.28}_{-0.28}$ similar to SDSS J1319+5202, the redshift error for this quasar translates into a small uncertainty of $\sigma(Q_{\text{eq}})$ = 1.02 Mpc owing to the Hβ emission line redshift. This constitutes a ≃ 12% relative error on $Q_{\text{eq}}$, which allows us to constrain the lifetime with good precision.

5.2.3 SDSS J1137+6237

The black histogram in Fig. 7 shows the marginalized posterior probability distribution for the lifetime of quasar SDSS J1137+6237. This quasar has the second biggest proximity zone ($Q_{\text{eq}} = 4.92 \pm 1.68$ Mpc) in our sample. Taking into account its relatively low luminosity, it is possible that it has a long lifetime. However, while this quasar has only ≃ 34% relative error on the proximity zone size (comparable to ≃ 27% error for SDSS J1319+5202), which, in principle, should provide good constraint on quasar lifetime, the resulting posterior distribution looks different than in case of SDSS J1319+5202 and HE2QS J1630+0435. Namely, the long tail of similar high posterior probabilities at $\log Q = 2.0$ is ≃ 2.5 times lower than the peak of the distribution, does not allow us to make a clear measurement of quasar lifetime, according to the criterion defined in Section 5.2.

This decreased constraining power at high $Q_0$ values arises from the fact that sensitivity of $R_{\text{eq}}$ measurements to quasar lifetime is limited by the value of the equilibration timescale $t_{\text{eq}}$ (see Section 4.1 for more details), which is $t_{\text{eq}} \approx 25$ Myr at $z \approx 4$. For lifetimes longer than the equilibration timescale $t_{\text{eq}} \geq t_{\text{eq}}$, proximity zone size $R_{\text{eq}}$ saturates and no longer increases with increasing $Q_0$ as shown in the left panel of Fig. 3. Consequently, the $R_{\text{eq}}$ PDFs for $t_{\text{eq}} \geq t_{\text{eq}}$ are comparable, as are the estimated likelihoods of models with $Q_0 \geq t_{\text{eq}}$. Therefore, our inference cannot distinguish between these models, which results in a tail in the posterior distribution, clearly seen in Fig. 7 for SDSS J1137+6237. Given the shape of its posterior, we can only quote a 95% lower limit on its lifetime. To this end we calculate the 5th percentile of the posterior distribution for quasar SDSS J1137+6237, which yields $\log Q = 2.0^{+0.36}_{-0.45}$.
5.2.4 The Remaining Quasars

It is apparent from Table 1 that for the remaining quasars the uncertainties \( \sigma(R_{pz}) \) arising from redshift error are a much larger fraction of their proximity zone sizes. The resulting broadening of the model \( R_{pz} \) PDFs (see Fig. 5) results in weaker constraints as illustrated by the flatter less peaked posterior distributions of these quasars in Fig. 7. As a result, following our definition of a measurement versus an upper limit, we can only provide 95 per cent upper limits on \( t_Q \) for these quasars. Although in one case this limit is particularly strong, namely the small proximity zone \( R_{pz} = 1.94 \pm 1.72 \) Mpc of HE2QS J2311–1417, combined with its relatively high luminosity yields a 95 per cent upper limit of \( \log_{10}(t_Q/\text{Myr}) < 0.31 \), strongly ruling out long lifetimes > 10 Myr.

Given the weaker constraints for the four quasars for which we only quote limits (HE2QS J2311–1417, SDSS J1317+6237, SDSS J1614+4859, & SDSS J1711+6052, see Table 1), we decided to run a joint analysis on all of them in order to constrain an average or effective quasar lifetime for this subsample. Even if lifetime has some dependence on quasar luminosity, the fact that the photon production rates for these four objects span a small dynamic range 0.5 dex (see Table 1) makes this a reasonable exercise. To conduct this joint analysis we simply multiply the likelihoods of models corresponding to the same combinations of \( (t_Q, \lambda_{HeII}) \) for each individual quasar in the subsample

\[
\mathcal{L}_{\text{joint}}(R_{pz}, i|\lambda_{HeII}) = \prod_{i=1}^{4} \mathcal{L}_{i}(R_{pz}, i|\lambda_{HeII}) .
\]

We then sample this joint likelihood with MCMC. The result is illustrated in Fig. 8, where we show the posterior for \( t_Q \) marginalized over \( \lambda_{HeII} \). We find that the effective lifetime for this subsample is \( \langle \log_{10}(t_Q/\text{Myr}) \rangle = 0.07 \pm 0.40 \), which appears consistent with the measured lifetimes for the two quasars SDSS J1319+5202 and HE2QS J1630+0435 (see Table 1). Note that interpreting the effective lifetime deduced by this ‘stacking’ approach can be a delicate issue if there is a broad distribution of the lifetimes (see the discussion in Section 5.1 of Khrykin et al. 2016), but in general it provides a reasonable representation of the average lifetime of a sample.

6 DISCUSSION

In this section we discuss systematics and several assumptions that went into our lifetime estimates and how they are relevant for placing robust constraints on quasar lifetime and initial He \( \alpha \) fraction in the IGM.

6.1 Uncertainties in the Photon Production Rate

We have demonstrated how the radial extent of the He \( \alpha \) proximity zone constrains the quasar lifetime. However, the size of the He \( \alpha \) proximity zone \( R_{pz} \) also depends on the quasar spectral energy distribution (SED, see Khrykin et al. 2016), which we have assumed to be determined perfectly by the apparent magnitudes of the quasars and an assumed spectral slope. In what follows we discuss how the uncertainties in quasar SED change the constraining power of our method.

As discussed in Khrykin et al. (2016), we approximate the quasar SED by a power-law, with specific photon production rate \( N_\nu \) at frequencies \( \nu \) above 4\( \text{Ry} \) given by

\[
N_\nu = N_{4\text{Ry}} \left( \frac{\nu}{4\text{Ry}} \right)^{-\left(1+\alpha_{\text{HeII}}\rightarrow\infty\right)} .
\]

It is apparent from equation (4) that the quasar SED is determined by: 1) the slope \( \alpha_{\text{HeII}}\rightarrow\infty \) of the SED at energies above 4 \( \text{Ry} \), and 2) the amplitude of the SED, given by the specific photon production rate at 4 \( \text{Ry} \), \( N_{4\text{Ry}} \).

First, the slope \( \alpha_{\text{HeII}}\rightarrow\infty \) determines the number of hard photons, and might affect the thermal and ionization states of IGM in quasar proximity, modifying the resulting He \( \alpha \) transmission profile and value of the \( R_{pz} \) (see Section 4.1). Unfortunately, this slope is currently not determined, and in this work we assumed that the same power law slope \( \alpha_{\text{HeII}}\rightarrow\infty = 1.5 \) governs the quasar spectrum for photon energies above 1 \( \text{Ry} \). However, in Khrykin et al. (2016) we investigated the impact of the variation in the slope \( \alpha_{\text{HeII}}\rightarrow\infty \) on the resulting He \( \alpha \) transmission profiles. In order to capture the effect of the slope we fixed the quasar specific luminosity \( \dot{N}_{\text{HeII}} \), and then freely varied the spectral slope in range \( \alpha_{\text{HeII}}\rightarrow\infty = 1.1 - 2.0 \). We found that due to weak dependence of the quasar He \( \alpha \) photoionization rate on \( \alpha_{\text{HeII}}\rightarrow\infty \), i.e. \( \Gamma_{\text{HeII}}^{QSO} \sim (\alpha_{\text{HeII}}\rightarrow\infty + 3)^{-1} \), the variations in the slope have at most a 10 per cent effect on \( \Gamma_{\text{HeII}}^{QSO} \). Consequently, the resulting He \( \alpha \) transmission profiles are essentially unaffected by these variations (see fig. 12 in Khrykin et al. 2016). For this reason, we conclude that neither the size of the He \( \alpha \) proximity zone \( R_{pz} \), nor the results of our MCMC inference will change significantly.

On the other hand, variations in the amplitude of the SED, \( N_{4\text{Ry}} \), might have a profound effect on inferred values of \( R_{pz} \) and the results of the MCMC inference (Khrykin et al. 2016). We estimate \( N_{4\text{Ry}} \) for each quasar in the data sample by scaling the observable quasar specific luminosity \( \dot{N}_{\text{HeII}} \) at the He \( \alpha \) ionization threshold of 1 \( \text{Ry} \) (determined by the corresponding i-band magnitudes and redshifts of the quasars in Table 1) to the He \( \alpha \) ionization threshold with a spectral slope \( \alpha_{\text{HeII}}\rightarrow\text{4Ry} \) (Hennawi et al. 2006; Khrykin et al. 2016). Therefore, the variations of the amplitude \( N_{4\text{Ry}} \) are inflicted by the uncertainty in \( \alpha_{\text{HeII}}\rightarrow\text{4Ry} \). Recently, there were several studies that reported although consistent, but slightly different slopes in the extreme-ultraviolet (EUV) at \( \lambda < 912\text{Å} \) (Scott et al. 2004; Shull et al. 2012; Lusso et al. 2015). Our fiducial value \( \alpha_{\text{HeII}}\rightarrow\text{4Ry} = 1.5 \) is slightly harder, but nevertheless consistent with the recent result from Lusso et al. (2015), who found \( \alpha_{\text{HeUV}} = 1.7 \pm 0.61 \) (see also Stevans et al. 2014). In what follows we explore how the uncertainty in \( \alpha_{\text{HeII}}\rightarrow\text{4Ry} \) changes the amplitude of quasar SED and how this affects the results of our inference. To that end, we adopt a much softer slope \( \alpha_{\text{HeII}}\rightarrow\text{4Ry} = 2.0 \), consistent with new measurement by Lusso...
Figure 9. One-dimensional posterior probability distributions of \( \log_{10}(t_q/\text{Myr}) \) from MCMC calculations of quasar SDSS J1319+5202 marginalized over the initial \( He \) fraction. The blue histogram shows the results of the inference performed on radiative transfer simulations with quasar spectral slope between 1 Ry and 4 Ry set to our fiducial value \( \alpha_{1\text{Ry} \rightarrow 4\text{Ry}} = 1.5 \) (same as in Fig. 7), whereas the red histogram illustrates the results for modified slope \( \alpha_{1\text{Ry} \rightarrow 4\text{Ry}} = 2.0 \) (see discussion in the text for more details).

et al. (2018). We create a new set of radiative transfer models (similar to the discussion in Section 3) for quasar SDSS J1319+5202, and perform the same analysis as in Section 4. Finally, we run the MCMC inference on the resulting PDFs for \( \alpha_{1\text{Ry} \rightarrow 4\text{Ry}} \approx 2.0 \) case.

Fig. 9 shows the resulting posterior probability distribution from the MCMC inference for quasar SDSS J1319+5202 with \( \alpha_{1\text{Ry} \rightarrow 4\text{Ry}} \approx 2.0 \), compared to our previous findings (see Fig. 7) with \( \alpha_{1\text{Ry} \rightarrow 4\text{Ry}} = 1.5 \). We infer the lifetime \( \log_{10}(t_q/\text{Myr}) = 0.17 \pm 0.39 \). It is apparent that the deduced lifetime of SDSS J1319+5202 is \( 0.4 \) dex longer than what we found in case of a harder spectral slope \( \alpha_{1\text{Ry} \rightarrow 4\text{Ry}} = 1.5 \) (see Section 5.2).

This result is expected given that the increase in \( \alpha_{1\text{Ry} \rightarrow 4\text{Ry}} \) reduced the amplitude of quasar SED \( N_{4\text{Ry}} \) by \( 0.4 \) dex (\( Q_{4\text{Ry}}^{\text{bol}} = I_{0}S_{4\text{Ry}}^{6.44 \times 10^{-1}} \)) in our radiative transfer models. Recall that we define the size of the proximity zone as the location where the smoothed transmission profile drops below 10 per cent for the first time. The transmission, on the other hand, is proportional to the evolution of the \( He \) fraction, governed by equation (Khrykin et al. 2016)

\[
x_{\text{HeII}} = x_{\text{HeII,eq}} + \left( x_{\text{HeII,0}} - x_{\text{HeII,eq}} \right) e^{-t_q/\tau_{\text{eq}}},
\]

where \( x_{\text{HeII,0}} \approx n_{\text{e}}\omega_{\text{HeII}}^{\text{t}_{\text{bkg}}/\text{HeII}} \) and \( x_{\text{HeII,eq}} \approx n_{\text{e}}\omega_{\text{HeII}} / \left( I_{\text{QSO,HeII}} + I_{\text{bkg,HeII}} \right) \) are the initial and equilibrium \( He \) n fractions. Here \( n_{\text{e}} \) and \( \omega_{\text{HeII}} \) are the electron density and recombination coefficient, respectively. The characteristic equilibration time-scale \( \tau_{\text{eq}} \) is given by

\[
t_{\text{eq}} \approx \left( n_{\text{e}}\omega_{\text{HeII}} + I_{\text{QSO,HeII}} + I_{\text{bkg,HeII}} \right)^{-1} \propto N_{4\text{Ry}}^{-1}.
\]

Therefore, according to equation (6), decreasing \( N_{4\text{Ry}} \) is equivalent to changing the time variable, and results in a re-scaling of our lifetime constraints by the same factor that \( N_{4\text{Ry}} \) has changed.

6.2 Comparison to Other Constraints on Quasar Lifetime

Our study of six \( z \approx 4 \) quasars suggests lifetimes of order \( t_q \approx 1 \) Myr. In what follows we discuss these results in the context of recent quasar lifetime measurements at \( z \sim 6 \), and their implications for the evolution of SMBH in the high-z Universe.

Eilers et al. (2017) analyzed the \( H_\perp \) proximity effect in the spectra of 34 \( z \approx 6 \) quasars and reported the discovery of three objects with exceptionally small \( H_\perp \) proximity zones that imply lifetimes \( t_q \leq 0.1 \) Myr, with one particular quasar shining for only \( t_q \leq 0.01 \) Myr (Eilers et al. 2018). These findings essentially constrain the fraction of young \( (t_q \approx 0.01 \) Myr) quasars to be 3 per cent. Moreover, Davies et al. in prep reported the upper limit on the total duty cycle of the most distant ULAS J1342+0928 quasar \((z = 7.54; \text{Bañados et al. 2018})\) to be \( t_q \leq 5.4 \) Myr, based on the IGM damping wing analysis. Consider a simple light bulb light curve model, in which the quasar is assumed to emit at constant luminosity for its entire lifetime \( t_q \). If one randomly samples such light curves with \( t_q \approx 1 \) Myr as suggested by our measurements, the probability of finding quasars that are as young as \( t_q \leq 0.01 \) Myr is 1 per cent, which is consistent with the \( 3 \) per cent young fraction determined by Eilers et al. (2017) given their statistical error on one object, suggesting that our results are in broad agreement with their discovery of young quasars.

However, such short lifetimes \( t_q \sim 1 \) Myr may be problematic given the constraints from quasar clustering and current theories about how SMBHs grow. Indeed, if one assumes a light bulb model for the quasar light curve, then under this assumption the lifetime \( t_q \) and the duty cycle \( t_{dc} \) are equivalent, and thus we measure the duty cycle as well. In this case our findings appear to be at odds with the high values of \( t_{dc} \) implied by the strong clustering quasars at \( z \approx 4 \) measured by Shen et al. (2007). For instance, White et al. (2008) modeled the Shen et al. (2007) clustering strength and found \( t_{dc} \approx 1 \) Gyr, but argued that these long duty cycles are not unexpected from the standpoint of black hole growth given a Salpeter time of \( t_q \approx 180 \) Myr (for Eddington ratios \( t_{bol}/L_{bol} \approx 0.25; \text{Kollmeier et al. 2006}) \). However, White et al. (2008) also argued that the dispersion \( \sigma \) in the relationship between quasar luminosity \( L \) and dark matter halo mass \( M_{\text{halo}} \) must then be less than 50 per cent (99 per cent confidence) for this high \( t_{dc} \). A decrease in duty cycle to \( t_{dc} \approx 100 \) Myr would already require an unphysically small amount of scatter \( \sigma \leq 10 \) per cent in the \( L - M_{\text{halo}} \) relation. Thus, if our quasars emit their radiation in one continuous episode such that \( t_q \approx t_{dc} \sim 1 \) Myr, there appears to be no easy way to reconcile our results with the clustering measurements. Furthermore, for our short inferred lifetimes and the assumption of a simple light curve, it would be impossible to grow \( \sim 10^9 M_{\odot} \) black holes in these quasar hosts without invoking super-Eddington accretion rates (Davies et al in prep).

One way to solve this problem would be to invoke a so-called flickering light curve model instead of a light bulb one (Ciotti & Ostriker 2001; Novak et al. 2011; Oppenheimer & Schaye 2013). In this picture the ultraviolet continuum emission from the quasar fluctuates as a result of either intrinsic changes in the accretion flow, or time variable obscuration along our line-of-sight. In general, the response of proximity zones to flickering light curves depends on the details of the light curve shape and the ionization state of the ambient IGM around the quasar. But the key point is that it takes the IGM an equilibration time-scale \( t_{eq} \approx 1/t_{bol} \) to respond to changes in the radiation field. For the sake of illustration, consider a toy model light curve whereby quasars emit continuously as light bulbs for \( t_{bol} \approx 1 \) Myr, but are then quenched for \( t_{off} \approx 10 \) Myr, and that this on/off behavior continues over a Hubble time \( t_{H} \). If \( He \) n in the IGM is highly ionized, then because \( t_{off} \) is comparable to the equilibration time \( t_{eq} \approx 30 \) Myr, gas in the IGM has enough time to recombine to ambient IGM ionization levels during the off periods. As a result, the
lifetimes we would infer from studying the proximity zones of active quasars would be $t_q \approx t_{\text{esc}}$, which however grossly underestimates the duty cycle $t_{dc} = (\ell_{\text{esc}}/t_{\text{esc}}/t_{\text{enc}})_{\text{He}} \approx 100$ Myr at $z \approx 4$. This toy model suggests that one can find a flickering light curve model which can satisfy our proximity zone constraints and still provide a sufficiently long duty cycle $t_{dc} \sim 100$ Myr required to grow the SMBH and closer to the values deduced from clustering. Although we note that the $z \sim 4$ quasar clustering results appear to tightly constrain the allowed light curves, since according to White et al. (2008) $t_{dc} \sim 100$ Myr would start to imply an unphysically small amount of scatter $\sigma$ in the relationship between quasar luminosity and and dark matter halo mass. More careful modeling of flickering light curves is clearly an interesting subject for future work.

7 CONCLUSIONS

We have measured the He II proximity zone sizes in the spectra of six $z \approx 4$ quasars. We performed cosmological hydrodynamical simulations, post-processed with 1D radiative transfer algorithm to analyze these He II proximity zones. We have used a fully Bayesian MCMC formalism to compare the distribution of He II of six simulations, post-processed with ii order to infer the quasar lifetimes, as well as the initial He II fraction in the IGM surrounding these quasars.

Our simulations indicate that proximity zone sizes are relatively insensitive to the He II fraction of the ambient IGM surrounding the quasars, which is confirmed by the results of our inference. We thus marginalize over the unknown $x_{\text{HeII}}$ to obtain constraints on quasar lifetime. We inferred $\log_{10}(t_q/\text{Myr}) = -0.20^{+0.36}_{-0.45}$ for quasar SDSS J1319+5202 and $\log_{10}(t_q/\text{Myr}) = 0.76^{+0.26}_{-0.28}$ for the HE2QS J1630+0435, but were able to put only 95 per cent limits on the lifetime of the remaining quasars due to large uncertainties in their systemic redshifts. In order to mitigate the effect of redshift error, we have also performed a joint analysis on four quasars and find $\log_{10}(t_q/\text{Myr}) = 0.07^{+0.40}_{-0.55}$ which is consistent with the two other measurements. All of our results thus seem to point to quasar lifetimes of $t_q \sim 1$ Myr at $z \sim 4$. We discussed this result in the context of other lifetime estimates at $z \geq 6$ that seem to deduce a comparable value, as well as the implication from quasar clustering that the duty cycles of $z \sim 4$ quasars are much longer.

Unfortunately, the large uncertainties inherent in using broad emission lines in the rest-frame UV/optical to determine quasar redshifts significantly limit the precision with which we can measure the lifetimes of individual quasars. An important direction for the future would be to obtain accurate systemic redshifts of these and other He II quasars via mm and sub-mm observations of CO and [C II] 158$\mu$m lines arising from cool gas reservoirs in the quasar host galaxies. Indeed, the much smaller systemic redshift errors ($\sim 50$ km s$^{-1}$) would enable lifetime measurements for all of the quasars considered here with a much smaller error of $\sim 0.10$ dex. We also note that a large sample of $\sim 20$ He II Ly$\alpha$ forest spectra exist at $z \approx 3$, and besides significantly improved statistics one also benefits from much better constraints on the He II fraction of the ambient IGM. We emphasize that the statistical techniques presented in this paper can also be applied to the measurements of quasar lifetime from the H I proximity effect at $z \approx 6$ (Eilers et al. 2018, Davies et al in prep). Furthermore, it would be interesting to explore statistical methods (for both He II and H I proximity zones) which uses the entire transmission profile (Davies et al. 2018) instead of just $R_p$. Finally, it would be interesting to perform a joint analysis of the line-of-sight He II proximity effect and the thermal proximity effect (resulting from He II photoelectric heating) in the H I Ly$\alpha$ forest (Khrykin et al. 2017) at $z \approx 4$, which will provide additional constraining power (especially for determining $x_{\text{HeII},0}$) as well as an independent check of our results.

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