Detecting and Characterizing Young Quasars. II. Four Quasars at z ∼ 6 with Lifetimes < 10⁴ Yr

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Abstract

The extents of proximity zones of high-redshift quasars enable constraints on the timescales of quasar activity, which are fundamental for understanding the growth of the supermassive black holes (SMBHs) that power the quasars’ emission. In this study, we obtain precise estimates for the ultraviolet (UV) luminous lifetimes of 10 quasars at 5.8 < z < 6.5. These objects were preselected to have short lifetimes based on preliminary measurements of their proximity zone sizes and were then targeted for high-quality follow-up submillimeter, optical, and infrared observations required to increase the measurements’ precision and securely determine their lifetimes. By comparing these proximity zone sizes to mock quasar spectra generated from radiative transfer simulations at a range of different lifetimes, we deduce extremely short lifetimes t_Q < 10⁴ yr for four objects in our sample, whereas the remaining quasars are consistent with longer lifetimes of t_Q > 10⁵ yr. These young objects with small proximity zones represent ≲10% of the quasar population as a whole. We compare our results in detail to other studies on timescales of quasar activity, which point toward an average lifetime of t_Q ∼ 10⁵ yr for the quasar population. This is consistent with finding newly turned-on quasars approximately 1%–10% of the time. These young quasars represent a unique opportunity to study triggering and feedback mechanisms of SMBHs, since the onset of their UV-luminous quasar phase happened only recently, and therefore traces of this process might still be observable.

Unified Astronomy Thesaurus concepts: Quasars (1319); Supermassive black holes (1663); Reionization (1383); Early universe (435); Intergalactic medium (813)

1. Introduction

Since the discovery of the first high-redshift quasars at z ≥ 6 nearly two decades ago (Fan et al. 2000, 2001), these distant luminous objects have been employed extensively as beacons through the cosmic web illuminating the diffuse intergalactic medium (IGM) and providing unique insights into the young universe. The evolution of the Lyman-series absorption features observed in the quasars’ spectra is one of the key observational probes of the physical properties of the intergalactic gas, which includes the majority of baryons in the universe.

The applications of these absorption features are abundant: for instance, the evolution of the Lyα and Lyβ opacities at high redshifts has provided invaluable constraints on the timing and morphology of the epoch of reionization (e.g., Fan et al. 2006; Becker et al. 2015; Eilers et al. 2018a, 2019; Bosman et al. 2018; Keating et al. 2020; Yang et al. 2020a). Statistical properties of the absorption lines in the Lyman-series forest such as the probability distribution function (e.g., Lee et al. 2015; Cieplak & Slosar 2017; Eilers et al. 2017b; Davies et al. 2018c) or the power spectrum (e.g., Palanque-Delabrouille et al. 2013; Irsic et al. 2017; Walthier et al. 2019; Boera et al. 2019) encode information about the physical properties of the absorbing gas, e.g., its thermal state and the ionizing UV background, whereas metal absorption lines in the unabsorbed part of the quasar spectra provide valuable clues about the chemical enrichment of the IGM (e.g., Simcoe et al. 2012; D’Odorico et al. 2013; Cooper et al. 2019; Becker et al. 2019; Simcoe et al. 2020).

However, while the aforementioned studies exploit the quasar spectra to constrain the properties of the intergalactic gas, we can in turn also explore the characteristics of the quasars by means of the IGM absorption features, since the quasars’ ionizing radiation illuminates the surrounding gas in their vicinity, injects heat, and changes its ionization state. Thus, by studying the properties of the IGM close to quasars, we can set constraints on the duration and intensity of the emitted ionizing radiation, as well as the obscuration fraction of the accreting black hole and the radiation geometry (e.g., Khyrkin et al. 2016, 2019; Eilers et al. 2017a, 2018b; Davies et al. 2019, 2020a; Schmidt et al. 2017, 2018; Bosman et al. 2020).

In this paper we will focus on constraining the timescales of the nuclear activity of quasars, i.e., the time during which the central supermassive black holes (SMBHs) actively accrete material from their environments, powering the quasar’s UV-luminous emission. We will distinguish between different timescales of quasar activity as follows: We define the lifetime of quasars t_Q (or equivalently their age) as the time at which the current UV-luminous quasar phase began, i.e., the quasar turned on at a time t_Q = t_0 in the past. In this case, t_0 denotes the time at which the radiation observed today was emitted, which corresponds to the quasar’s emission a look-back time ago. However, quasar activity may be episodic with alternating epochs of luminous quasar and quiescent phases. The quasar’s duty cycle indicates the integrated time over the age of the universe at that epoch that galaxies shine as active quasars, and thus it provides an upper limit on the lifetime. A quasar’s
lifetime and duty cycle are equivalent in the case of a simple
“light-bulb” light-curve model, in which the quasar is assumed
to emit at constant luminosity for its entire lifetime.

These timescales of quasar activity represent important
parameters for understanding the growth of their accreting
SMBHs, which can have masses up to \( \gtrsim 10^9 M_\odot \) as early as
\(<1\) Gyr after the Big Bang (e.g., Mortlock et al. 2011;
Mazzucchelli et al. 2017; Bañados et al. 2018; Yang et al.
2020b; Wang et al. 2021). Assuming a constant supply of
fueling material, black holes grow exponentially during the
lifetime of the quasar from an initial black hole seed with a
mass \( M_{\text{seed}} \), i.e.,

\[
M_{\text{BH}}(t_Q) = M_{\text{seed}} \cdot \exp \left( \frac{t_Q}{t_s} \right),
\]

The growth of the SMBHs occurs on a characteristic timescale,
which is called the “Salpeter” time \( t_s \) (Salpeter 1964) or e-
folding time, i.e.,

\[
t_s = 0.45 \left( \frac{\epsilon}{1 - \epsilon} \right) \left( \frac{L_{\text{bol}}}{L_{\text{Edd}}} \right)^{-1} \text{ Gyr},
\]

where \( \epsilon \) denotes the radiative efficiency of the accretion with
a fiducial value of \(~10\%\) for thin accretion disks (Shakura &
Sunyaev 1973), and \( L_{\text{bol}} \) describes the bolometric luminosity
of the quasar, which has a theoretical upper limit of the
Eddington luminosity \( L_{\text{Edd}} \). In order to grow an SMBH with a
mass of \(~10^9 M_\odot\) from an initial black hole seed from a stellar
remnant of a Population III star, i.e., \( M_{\text{seed}} \sim 100 M_\odot \) (e.g.,
Madau & Rees 2001), it requires at least 16 e-foldings, i.e.,
\( t_Q \gtrsim 7 \times 10^8 \) yr, even if the quasars accrete continuously at the
Eddington limit (e.g., Volonteri 2010, 2012). However, it is
currently unknown whether quasars obey this exponential light
curve, or if other physics related to the triggering of quasar
activity and the supply of fueling material complicate this
simple picture, which would give rise to more complex
“flickering” light curves (e.g., Di Matteo et al. 2005; Springel
et al. 2005; Hopkins et al. 2005b; Novak et al. 2011;
Schawinski et al. 2015).

Quasar lifetimes can be estimated by different methods.
Properties of the IGM such as the opacity, ionization state, and
temperature in the vicinity of a quasar react to any changes in a
quasar’s accretion rate with a time lag. Such an ionization “echo”
leaves an imprint on the surrounding IGM, which can be
observed, for instance, in the Ly\( \alpha \) opacity of a background
source at small impact parameters (Adelberger 2004; Hennawi
et al. 2006; Visbal & Croft 2008; Schmidt et al. 2019).
Similarly, the time lag between the onset of the quasar’s
radiation and its arrival at nearby Ly\( \alpha \)-emitting galaxies
(LAEs) can be utilized to constrain the lifetime of quasars
(Trainor & Steidel 2013; Bosman et al. 2020). The ratio of the
number density of dark matter halos hosting an active quasar
and the full numbers or halos that could host halos inferred
from quasar clustering studies allows for constraints on the
quasars’ duty cycle (e.g., Martini & Weinberg 2001; Haiman &
Hui 2001; Shen et al. 2007; White et al. 2008; Conroy &
White 2013).

In this study we estimate the lifetime of high-redshift quasars
by means of the extents of their Ly\( \alpha \) proximity zones observed
in their rest-frame UV spectra along the line of sight to the
quasars. Proximity zones are the regions of enhanced
transmitted flux close to the quasars (Bajtlik et al. 1998), which
are sensitive to the lifetime of quasars because the intergalactic
gas has a finite response time to the quasars’ radiation (Bolton &
Haehnelt 2007; Khrykin et al. 2016; Eilers et al. 2017a;
Davies et al. 2020a, 2020b; Ishimoto et al. 2020). By applying
this method to a data set of 31 \( z \sim 6 \) quasars, we previously
discovered a population of very young quasars, which imply
extremely short lifetimes of \( t_Q \lesssim 10^5 – 10^6 \) yr (Eilers et al.
2017a, 2018b). These young objects pose significant challenges
for the growth of SMBHs at high redshift, since their lifetimes
are several orders of magnitude shorter than the time required
for the exponential growth of the black holes described in
Equations (1) and (2).

Here we estimate the lifetime of quasars for 10 high-redshift
objects, which were preselected to likely have very short
lifetimes, i.e., \( t_Q \lesssim 10^5 \) yr, in order to establish a statistically
significant sample of known young quasars, as well as to
estimate the fraction of young quasars within the quasar
population at large. To this end, in Eilers et al. (2020, hereafter
Paper I) we have obtained a multiwavelength data set for this
quasar sample to precisely measure the extents of their
proximity zones, which is summarized in Section 2. By
comparing these measurements to simulated quasar spectra at
different lifetimes from 1D radiative transfer (RT) simulations
(Section 3), we will obtain precise lifetime estimates
(Section 4). We will compare our results to other studies of
quasar activity timescales from the literature (Section 5) and
discuss the implications of very short quasar lifetimes
(Section 6), before summarizing our findings (Section 7).

Throughout this paper, we assume a flat \( \Lambda \)CDM cosmology of
\( h = 0.685, \Omega_m = 0.3, \Omega_\Lambda = 0.7 \).
redshifts even when estimated based on submillimeter or FIR emission lines. Thus, we conservatively estimate a systematic uncertainty of the redshift estimate of $\Delta v \approx 100$ km s$^{-1}$, i.e., $\Delta z \approx 0.0023$ at $z \approx 6$, which is an uncertainty comparable to the kinematics of the host galaxies (e.g., Neelameggha et al. 2019; Venemans et al. 2019). We ignore statistical uncertainties in the emission-line peak ($\Delta v \lesssim 10$ km s$^{-1}$), as they are much smaller than the systematic uncertainty. This redshift uncertainty corresponds to a systematic uncertainty on the proximity zone of $\Delta R_p \approx 0.14$ pMpc for a quasar at $z \approx 6$.

For quasars without available submillimeter observations or nondetections we estimated the systemic redshift from the Mg II broad emission line. However, this line is systematically blueshifted compared to the systemic redshift of the quasar (e.g., Mazzucchelli et al. 2017; Venemans et al. 2016; Meyer et al. 2019; Schindler et al. 2020), and thus we account for these systematic uncertainties and shift the redshift estimate by $\Delta v$ (Mg II-[C II]) = $-391^{+256}_{-435}$ km s$^{-1}$ to the systemic frame (Schindler et al. 2020).

The optical and near-infrared (NIR) spectra in our data sample were observed with the X-Shooter echelle spectrograph on the Very Large Telescope (VLT) and the DEep Imaging Multi-Object Spectrograph (DEIMOS) on the Keck II telescope. The spectra were reduced, combined, and flux-calibrated using PyPelt (Prochaska et al. 2020), a newly developed algorithm for semi-automated reduction of astronomical spectroscopic data.

In order to calculate the sizes of the proximity zones $R_p$, we normalize the spectra by their continuum emission, which is estimated by means of a principal component analysis (PCA) trained on low-redshift quasar spectra (e.g., Suzuki 2006; Pâris et al. 2011; Davies et al. 2018b; Bosman et al. 2021). The coefficients of the principal components for the continuum model are estimated on the unabsorbed part of the quasar spectra, i.e., redward of the Ly$\alpha$ emission line, and then projected onto a set of principal components blueward of the Ly$\alpha$ emission line, where the $z \geq 6$ quasar spectra are affected by IGM absorption (see Paper I for details). The continuum-normalized flux is then smoothed with a 20 Å wide (observed frame) boxcar function, which corresponds to $\sim 1$ pMpc or a $\sim 700$ km s$^{-1}$ window at $z = 6$. The location at which the smoothed flux drops below the 10% transmission level defines the end of the quasars’ proximity zones (Fan et al. 2006; Carilli et al. 2010; Eilers et al. 2017a). In Paper I we carefully search for any dense absorption systems such as damped Ly$\alpha$ systems (DLAs) or Lyman limit systems (LLSs) in the close vicinity of the quasars to exclude a premature truncation of the proximity zones. Such absorption systems are not modeled in our simulations (see Section 3) and thus need to be excluded from our sample for the lifetime analysis. To this end we stacked the spectral regions that would show metal absorption lines associated with a hypothetical LLS at the edge of the proximity zone and compared this stack to the composite spectrum of 20 low-redshift LLSs from Fumagalli et al. (2013). The authors of this study conclude that the gas giving rise to the composite LLS spectrum is likely metal-poor, i.e., [Fe/H] $\lesssim -1.5$. We did not find any evidence of such metal-poor LLSs truncating the quasar proximity zone sizes, although the presence of very highly metal-poor or pristine systems cannot be excluded.

All measurements of the systemic redshifts and the proximity zone sizes are shown in Table 1.

3. Radiative Transfer Simulations

In order to interpret the proximity zone measurements, we conduct a series of RT simulations of the effect of ionizing radiation emitted by the quasar, which ionizes the IGM along the line of sight (Bolton & Haehnelt 2007). We apply the 1D RT code by Davies et al. (2016) to skewers from the cosmological hydrodynamical Nyx simulation within a box of 100 Mpc h$^{-1}$ on a side (Almgren et al. 2013; Lukić et al. 2015). The simulation includes 4096 baryonic (Eulerian) grid elements and dark matter particles and was designed for precision cosmology studies of the diffuse gas in the IGM. The RT code computes the time-dependent ionization and recombination rates of six particle species, i.e., $e^+$, H I, H II, He I, He II, and He III, as well as photoionization heating from the quasar’s radiation itself and the associated heating and cooling of the intergalactic gas due to the expansion of the universe and inverse Compton cooling off the cosmic microwave background (CMB). Intergalactic gas that is self-shielding from the UVB is treated via the method presented in Rahmati et al. (2013), whereas the self-shielding to the quasar light is treated self-consistently in the RT simulations.

The quasar’s escape fraction of ionizing UV photons is assumed to be unity. This is consistent with measurements at lower redshift, where such measurements of the escape fractions are easily possible, since there is no or only very little Lyman-series forest absorption. Stevans et al. (2014), for instance, conducted a measurement for quasars at $z < 1.5$ and found no break in the quasar spectra at the Lyman limit with an optical depth $\tau < 0.01$, i.e., $f_{esc} > 99\%$. At higher redshifts such measurements are more challenging owing to the higher IGM absorption. However, Worseck et al. (2014) constructed stacked quasar spectra at $z \sim 5$ in order to measure the mean free path of Lyman continuum photons, which also do not show any break around the Lyman limit, similarly indicating high escape fractions.

We assume the luminosity-dependent bolometric correction from $M_{1450}$ given in Table 3 of Runnoe et al. (2012) and convert $M_{1450}$ to ionizing luminosity using the spectral energy distribution (SED) by Lusso et al. (2015). This SED assumes a spectral index of $\alpha_\nu = -1.7$. We discuss the influence of the chosen SED on our results in Section 4.1.

For each quasar we take 10000 skews of density, temperature, and peculiar velocity, which are drawn from the centers of the most massive dark matter halos in the Nyx simulation. In order to avoid interpolation errors, we extrapolate six sight lines from each halo along the $\pm x$, $y$, and $z$-axes. The halos have masses between $4 \times 10^{13} M_\odot \lesssim M_{halo} \lesssim 3 \times 10^{12} M_\odot$; however, our results are nearly independent of the chosen host dark matter halo mass (see also Keating et al. 2015). We have Nyx simulation outputs at $z = 6$ and $z = 6.5$ available, from which we choose the output closest to the quasar’s redshift $z_{em}$ and rescale the physical densities by $(1 + z_{em})^3$.

The ionization state of the IGM before the quasar turns on is given by post-reionization conditions and thus is considered to be highly ionized, i.e., with a neutral fraction of $x_{HI} \sim 10^{-4}$. Furthermore, we assume an ultraviolet background (UVB) radiation with an ionization rate of $\Gamma_{UVB} = 2 \times 10^{-13}$ s$^{-1}$, which is consistent with observations of the Ly$\alpha$ forest opacity (Fan et al. 2006; Wyithe & Bolton 2011; Davies et al. 2018c; Yang et al. 2020a). Note that our Nyx simulation does not model the inhomogeneous reionization process, but rather assumes that reionization happens instantaneously at $z \sim 10$,.
The columns show the name of the quasar, its systemic redshift estimate with its systemic uncertainty and the emission line it is derived from, its absolute magnitude $M_{1450}$, and the measurement of the size of the proximity zone. The last column shows the median and 16th–84th (2.5th–97.5th) percentile lifetime estimates. Note that all lifetime estimates have a systematic uncertainty of $\sigma_{\text{sys,log10}Q} \approx 0.4$ (see Section 4.1 for details).
based on the broad Mg II emission line and thus were shifted to the systemic redshift frame have an asymmetric uncertainty on their proximity zone size estimates. For those objects we randomly draw from the measured velocity offsets between the MgII and [C II] emission lines of 28 $z \geq 6$ quasars in Schindler et al. (2020), which changes each simulated proximity zone measurement by $\Delta R_p = \Delta v / H(z)$, where $H(z)$ denotes the Hubble parameter at the quasars’ redshifts.

The likelihood is $L = P(R_p | t_Q)$, and we take a flat logarithmic prior on $t_Q$. We perform a 2D kernel density estimation (KDE) on the distribution of $R_p$ as a function of $\log_{10}(t_Q/\text{yr})$ (see also Khrykin et al. 2019) and evaluate the 2D distribution at $R_p$ to obtain a posterior probability distribution function for each quasar’s lifetime marginalized over the proximity zone measurement uncertainty. The dotted lines in the middle and right panels indicate that the proximity zone size evolution beyond $\log_{10}(t_Q/\text{yr}) > 8$ should be taken with caution owing to the limitations in our modeling procedure described in Section 3.1.

Figure 1. Lifetime estimates for the four young quasars in our sample. Left panels: continuum-normalized quasar spectra around the Ly$\alpha$ emission line (black) and their noise vector (gray), which have been inverse-variance smoothed with a 3-pixel filter. The proximity zones extend between the systemic redshift estimate of the quasars, shown by the red solid lines, and the red dashed lines indicating the end of the proximity zone. Middle panels: evolution of proximity zone sizes with quasar lifetime from RT simulations. The proximity zone measurements and their 1σ (68th percentile) uncertainties are indicated by the red dashed lines and shaded regions. Right panels: posterior probability distribution of the quasar’s lifetime marginalized over the proximity zone measurement uncertainty. The dotted lines in the middle and right panels indicate that the proximity zone size evolution beyond $\log_{10}(t_Q/\text{yr}) > 8$ should be taken with caution owing to the limitations in our modeling procedure described in Section 3.1.
Figure 2. Same as Figure 1, but for the remaining quasars in our sample.
in the right panels of Figures 1 and 2. We take the median of this posterior probability distribution as the best lifetime estimate with uncertainties given by the 68th (95th) percentile.

Note that we adopt a lower (or upper) limit on the lifetime estimate if the probability exceeds an arbitrarily chosen threshold of $P > 0.15$ at the boundaries of the considered range of lifetime values, which are set by our chosen prior. The lower boundary of our prior, i.e., $t_0 \geq 10^4$ yr, is set because most of the analyzed quasars are known for $\geq 10^4$ yr, whereas the upper boundary of our prior, i.e., $t_0 \leq 10^8$ yr, approximately corresponds to the age of the universe at the quasars’ redshifts. Table 1 shows the lifetime estimates for all quasars in our sample.

We find four quasars in our data sample for which we estimate a very short lifetime, i.e., $t_0 < 10^3$ yr (Figure 1). For the remaining six quasars our estimates indicate longer lifetimes of $t_0 \gtrsim 10^7$ yr (Figure 2). These quasars ended up in our data sample despite the preselection for potentially young quasars because their preliminary redshift estimates based on template fitting were scattered toward lower redshifts and thus smaller proximity zones. The more precise estimates based on submillimeter emission lines or the MgII emission line that we obtained in Paper I reveal a higher systemic redshift, and thus their proximity zones are larger and their lifetime estimates longer.

4.1. Sources of Systematic Uncertainty

Various sources of uncertainty in our modeling procedure can affect our results, which we will discuss now. For instance, the choice of SED affects the number of emitted ionizing photons from the quasar. Our fiducial SED assumes a spectral index of $\alpha_{\nu} = -1.7$ (Lusso et al. 2015). In order to estimate the influence of the SED on our results, we alter the spectral index by $\Delta \alpha_{\nu} = 0.5$, i.e., $\alpha_{\nu} = -1.2$ and $\alpha_{\nu} = -2.2$, and estimate the quasars’ lifetimes for the modified SED. This alters our lifetime estimates slightly, and thus the systematic uncertainty on the lifetime estimates introduced by the choice of the quasars’ SED is $\Delta \log_{10} t_0 \lesssim 0.3$ (see Figure 4 in Appendix).

Furthermore, the choice of the ionizing background $\Gamma_{\text{UVB}} = 2 \times 10^{-13}$ s$^{-1}$ also influences the quasar lifetime estimates. Davies et al. (2018a) have shown that patches with $\sim 4$ times lower $\Gamma_{\text{UVB}}$ can exist at $z \sim 6$. To this end we evaluate the influence that a weaker ionizing background of $\Gamma_{\text{UVB}} = 4 \times 10^{-14}$ s$^{-1}$ would have on our results and find that it introduces a systematic uncertainty of $\Delta \log_{10} t_0 \approx 0.2$. Note, however, that the regions around quasars within a few Mpc are likely to have a relatively high UVB compared to the mean UVB (Davies 2020), in which case our choice of the mean UVB would be conservative. Thus, the combined, i.e., added in quadrature, systematic uncertainties on the quasar lifetime estimates arising from the choice of SED and the ionizing background are $\sigma_{\text{sys, log}_{10} t_0} \approx 0.4$.

Some recently published late reionization models predict that $\geq 30\%$ of the cosmic volume is occupied with neutral gas fractions of $x_{\text{HI}} \geq 0.1$ as late as $z \sim 6$ (Kulkarni et al. 2019; Keating et al. 2020). If the quasars at $z \sim 6$ would indeed still reside in large neutral patches, this could potentially influence our analysis. However, if the intergalactic gas surrounding the quasars is indeed still mostly neutral, it should imprint a damping wing on the Ly$\alpha$ emission line (Miralda-Escudé 1998).

While such damping wings have to date only been detected in quasars at $z \gtrsim 7$ (Greig et al. 2017; Davies et al. 2018b; Wang et al. 2020; Yang et al. 2020b), we cannot rule out securely the existence of highly neutral gas around the young quasars. Nevertheless, a still partially incomplete reionization process with remaining neutral patches, fluctuations in the IGM temperature, or a varying mean free path of ionizing photons may affect the proximity zones, but such modeling will be part of future work.

5. Comparison to Previous Studies

Many other studies have set constraints on the timescales of quasar activity with a variety of different methods. We will summarize some of the results from the literature and distinguish between constraints obtained by analyzing the proximity zones in the observed spectra along the line of sight (Section 5.1), by studying the ionization echo of the quasars’ radiation (Section 5.2), or constraints on the duty cycle of quasars from clustering studies (Section 5.3).

5.1. Lifetime Constraints from Quasar Emission along the Line of Sight

A similar approach to obtain quasar lifetime estimates to the one presented in this work has been applied to quasars at $z \gtrsim 7$ (Davies et al. 2019). While the IGM at $z \sim 6$ is already highly ionized, at $z \gtrsim 7$ it still contains a significant neutral gas fraction since the epoch of reionization is not yet completed. Thus, quasar spectra at $z \gtrsim 7$ exhibit a damping wing around the Ly$\alpha$ emission line owing to the increased neutral gas fraction of the IGM (Miralda-Escudé 1998). The shape and strength of these damping wings provide information about the total number of ionizing photons that have been emitted into the IGM, which can be used to obtain estimates on the integrated lifetime, i.e., the quasars’ duty cycle. Applying this method to four quasars at $z \gtrsim 7$ resulted in estimates of $t_0 \lesssim 1$ Myr (Davies et al. 2019; Wang et al. 2020; Yang et al. 2020b; F. B. Davies et al. 2021, in preparation).

Quasars at $z \sim 3–4$ exhibit a proximity zone in the HeII Ly$\alpha$ forest (e.g., Hogan et al. 1997), which provides constraints on the lifetime of quasars similarly to the proximity zones in the H1 Ly$\alpha$ forest at $z \sim 6$. However, due to the lower photoionization rate at the HeII ionizing edge (Shull et al. 2004), the timescale to obtain ionization equilibrium is longer, i.e., $t_{\text{eq,HeII}} \sim 3 \times 10^7$ yr, and thus the extent of the proximity zone remains sensitive to longer quasar lifetimes before reaching ionization equilibrium (Khrykin et al. 2016). Khrykin et al. (2019) applied this method to obtain lifetime constraints for six quasars at $z \sim 4$, for which they estimate lifetimes of $t_0 \sim 10^6–10^7$ yr (see also Worseck et al. 2021; Khrykin et al. 2021).

An estimate of the average effective lifetime of the $z \sim 6$ quasar population has been obtained by stacking the proximity zones of a luminosity-selected, i.e., unbiased toward young ages, sample of 15 quasars (K. A. Morey et al. 2021, in preparation). By comparing the stacked transmitted flux profile around quasars, selected solely based on their absolute magnitude, i.e., $-26.6 > M_{1450} > -27.4$, and systemic redshifts, i.e., $5.8 < z < 6.5$ based on submillimeter emission lines, to the stacked profile of simulated data sets from RT simulations at different lifetimes, they obtain a lifetime estimate for the whole quasar population of $\log_{10}(t_0/\text{yr}) = 5.7^{+0.5}_{-0.3}$.
Finally, Davies et al. (2020b) performed a similar analysis to ours on the proximity zone of the hyperluminous $z \approx 6.3$ quasar SDSS J0100+2802, one of the young quasars found in Eilers et al. (2017a), to test the hypothesis that it could be strongly gravitationally lensed (Fujimoto et al. 2020). Based on the size and shape of the quasar’s proximity zone, they exclude a strong magnification and confirm the young age of the object $\log_{10}(t_0/\text{yr}) = 4.28_{-0.15}^{+0.61}$.

All lifetime constraints based on H I or He II proximity zones measured along the line of sight are shown in Figure 3 as blue and red shaded data points, respectively.

5.2. Lifetime Constraints Based on the Quasars’ Ionization Echo

The time lag between the onset of a quasar’s ionizing radiation and its arrival at a nearby galaxy or its crossing of a background sight line can also be used to constrain the duration of the quasar’s emission, as well as its geometry and nuclear obscuration.

For instance, Schmidt et al. (2018) studied the He II transverse proximity effect, i.e., the enhanced flux transmission in the He II Ly$\alpha$ forest in a spectrum of a background quasar due to the ionizing radiation of a quasar in the foreground (see also Jakobsen et al. 2003). From the analyzed objects, however, only one shows a clear transmission spike allowing constraints on the quasar age, but for three other ones they do not detect transmission, from which they conclude that these quasars could either be young, i.e., $t_0 \lesssim 10$ Myr, or highly obscured (see also Schmidt et al. 2017). Similarly, Kirkman & Tytler (2008) study the transverse proximity effect in the H I Ly$\alpha$ forest by means of close quasar pairs at $z \approx 2.2$ and conclude that quasar lifetimes of less than a million years can explain the absorption pattern they observe in the spectra of the background quasars at the location of the foreground objects.

Bosman et al. (2020) recently set constraints on the lifetime of a quasar at $z \approx 5.8$ by studying the emission-line profiles from nearby LAEs. The observed line profiles are expected to be double-peaked if the galaxies are embedded in a highly ionized IGM, whereas if the quasar’s radiation has not yet reached their location and the IGM is less ionized, the blue peak would be absorbed. By modeling the time lag between the quasar and the surrounding galaxies, they constrain the lifetime of the quasar to be $2.3 \times 10^7 \lesssim t_0 \lesssim 2.2 \times 10^9$ yr.

A similar study by Trainor & Steidel (2013) investigated the fluorescent emission of LAEs due to reprocessing of the ionizing radiation from a nearby quasar. Their study of eight hyperluminous quasars at $2.5 < z < 2.9$ allows joint constraints on the geometry and history of the emitted ionizing radiation, from which they estimate an average lifetime of $10^7 \lesssim t_0 \lesssim 2 \times 10^9$ yr.

Lower limits on the lifetime of quasars can be derived from the extended Ly$\alpha$ nebulae, since continuous emission is required to sustain the nebular emission found ubiquitously around $z \sim 2$–4 quasars (Hennawi & Prochaska 2013; Borisova et al. 2016a; Arrigoni Battaia et al. 2019) and around a majority of $s \sim 6$ quasars (Farina et al. 2019; Drake et al. 2019). Giant
nebulae extending up to 450 kpc distance from the quasar hosts provide evidence for sustained quasar lifetimes \( \gtrsim 1 \) Myr (Cantalupo et al. 2014; Hennawi et al. 2015).

At very low redshifts around \( z \lesssim 0.1 \) the discovery of extended highly ionized nebular regions around quiescent galaxies, such as “Hannys Voorwerp” (Lintott et al. 2009), has led to constraints on the timescales of quasar activity around currently inactive, quiescent objects. The presence of high-ionization emission lines suggests photoionized gas from an active galactic nucleus (AGN), but the optical spectrum does not reveal a currently active nuclear core. Thus, Keel et al. (2012) argue that the AGN luminosity must have dropped significantly in the recent past and that the observed ionized nebula manifests as the light echo of the faded AGN. Based on the extents of the ionized regions and the number of faded to nonfaded AGNs, they estimate that the nuclear active phase in these galaxies must have lasted for \( 0.2 \sim 2 \times 10^5 \) yr (see also Schawinski et al. 2015; Sartori et al. 2018).

A related argument has been brought forward by Oppenheimer et al. (2018), who simulate the highly ionized circumgalactic medium around \( z \sim 0.2 \) galaxies, to reproduce the strong abundance of O VI absorbers observed in the COS-Halos survey (Tumlinson et al. 2011). They argue that these galaxies likely hosted an AGN in their past with a lifetime of \( t_Q \lesssim 10^5 \) yr, which is shorter than the recombination time of O VI, i.e., \( f_{\text{rec}} \sim 10^7 \) yr, to explain the observed high O VI abundance. However, other studies have explained the abundance of such systems without invoking AGN photoionization (e.g., McQuinn & Werk 2018; Stern et al. 2018).

Constraints on the lifetime of quasars based on the light echo of their ionizing radiation are shown in Figure 3 as green and yellow shaded data points.

5.3. Constraints on the Quasar Duty Cycle from Clustering

The duty cycle of quasars can be estimated from the ratio of the number density of dark matter halos hosting an active black hole to the total number of halos that could host quasars within the luminosity range of a given sample. Since more massive halos have a higher clustering bias (Kaiser 1984; Tinker et al. 2010), the observed clustering of quasars determines the characteristic mass of their host halos. The abundance of such halos compared to the number density of quasars they host results in an estimate of the fraction of time that galaxies shine as luminous quasars (e.g., Efstathiou & Rees 1988; Haiman & Hui 2001; Martini & Weinberg 2001; White et al. 2008; Conroy & White 2013).

This approach to infer the duty cycle of quasars by measuring their number density and clustering strength has been adopted by several groups making use of the large quasar samples at \( 2 \lesssim z \lesssim 4 \), such as the Sloan Digital Sky Survey (SDSS; Shen et al. 2007, 2009; Shankar et al. 2010), the Baryon Oscillation Spectroscopic Survey (BOSS; White et al. 2012), and most recently the extended-BOSS (eBOSS) sample (Eftekharezadeh et al. 2015; Laurent et al. 2017). These results are broadly consistent with duty cycles of \( \sim 10^4 \sim 10^8 \) yr, apart from Shankar et al. (2010), who infer a shorter duty cycle for lower-redshift quasars at \( 0.4 \lesssim z \lesssim 2.5 \), although their measurements do not securely exclude longer duty cycles.

Yu & Tremaine (2002) use the velocity dispersion of early-type galaxies in SDSS to estimate the local black hole mass density, which they find to agree with the black hole mass density accreted during optically luminous quasar phases estimated from quasar luminosity functions. They obtain an estimate of the duty cycle of quasars of \( \sim (3 \sim 13) \times 10^7 \) yr, which is comparable to the Salpeter time (Equation (2)).

A slightly different approach to measure the duty cycle of quasars at \( z \sim 6 \) was recently attempted by Chen & Gnedin (2018), who made use of the [C II] gas dynamics in quasar host galaxies observed with ALMA (Decarli et al. 2018), from which they estimate the dark matter halo masses of quasar hosts. Unfortunately, their results are strongly dependent on the underlying assumptions of how the [C II]-emitting gas populates the dark matter halos, but they derive an upper limit on the quasar duty cycle of \( \lesssim 10^{-3} \) yr at \( z \sim 6 \).

In Figure 3 the constraints from studies of the duty cycle of quasars and their host galaxies are shown as gray and purple data points.

6. Discussion

6.1. Implications of Short Quasar Lifetimes

The comparison to previous work reveals that multiple studies point toward an average lifetime of \( t_Q \sim 10^6 \) yr for the quasar population at large. While many of the aforementioned studies constrain the duty cycle and lifetime of an ensemble of quasars, inferring quasar lifetimes from the extents of proximity zones offers the possibility to infer the lifetime of individual objects.

In this paper we confirmed the short lifetimes of four quasars, which increases the number of confirmed young quasars to seven in total, keeping in mind the three previously identified young objects (Eilers et al. 2017a, 2018b; Davies et al. 2020b; Andika et al. 2020). This confirms the fraction of young quasars within the whole quasar population to be \( 5% \sim f_{\text{young}} \lesssim 10% \) reported in Paper I. Thus, when assuming an average lifetime of the quasar population of \( t_Q \sim 10^6 \) yr, we expect to see quasars with short lifetimes of \( t_Q \sim 10^4 \sim 10^5 \) yr \( \sim 1 \sim 10\% \) of the time when randomly sampling a light-bulb light curve with \( t_Q \sim 10^6 \) yr. Given the statistical error on the small sample size, this implies that the estimated fraction of young quasars \( f_{\text{young}} \) is approximately consistent with an average lifetime of the overall quasar population of \( t_Q \sim 10^6 \) yr, which various studies agree on to be the preferred value at different redshifts ranging from \( 3.0 \lesssim z \lesssim 7.5 \) (e.g., Kryshkin et al. 2016; Davies et al. 2019; Kryshkin et al. 2021; K.A. Morey et al. 2021, in preparation).

It is interesting to note that the fraction of confirmed young quasars within the quasar population as a whole is \( \sim 4% \) for objects at \( z < 6.1 \) and \( \sim 6% \) for those at \( z > 6.1 \). Keeping in mind the still preliminary statistics due to the small total number of confirmed young quasars, this suggests that there is no significant redshift evolution of the young quasar fraction within the probed redshift range.

Assuming light-bulb light curves, the inferred short average quasar lifetime of \( t_Q \sim 10^6 \) yr poses significant challenges to current models for the formation and growth of SMBHs in the center of the quasars’ host galaxies. The quasars’ optical and NIR spectra reveal that most observed luminous \( z \sim 6 \) quasars host SMBHs of \( \sim 10^9 M_\odot \) (e.g., Mazzucchelli et al. 2017; Schindler et al. 2020). Based on arguments laid out in Section 1, these quasars must have been accreting for \( t_Q > 700 \) Myr, when assuming a radiative efficiency of \( \epsilon \sim 0.1 \) (see red shaded region in Figure 3). Thus, in order to reduce the Salpeter time to comply with the shorter observed
average quasar lifetimes of $t_Q \sim 10^6$ yr, our results might provide evidence for highly radiatively inefficient accretion rates, i.e., $\epsilon \sim 0.001$, as expected for “super-Eddington” or “hyper-Eddington” accretion disks (e.g., Inayoshi et al. 2016; Begelman & Volonteri 2017). The tension between the expected and observed quasar lifetimes can further be alleviated when assuming flickering quasar light curves with multiple episodes of quasar accretion instead of light-bulb light curves, as discussed in Section 6.2.

An alternative explanation for the existence of SMBHs in high-redshift quasars despite their short UV-luminous lifetimes could be that a majority of the black hole growth happens in highly obscured, dust-enshrouded environments (e.g., Yu & Tremaine 2002; Hopkins et al. 2005a, 2008; Eilers et al. 2018b; Davies et al. 2019). The latter scenario would imply the presence of a large fraction of obscured quasars in the high-redshift universe that has not yet been observed (but see Vito et al. 2018, 2019).

6.2. Effects of Flickering Quasar Light Curves

The proximity zones of quasars are mostly sensitive to the most recent UV-luminous episode of quasars, and thus some of the tension between the short lifetimes of the quasars and the time required to grow the SMBHs can be alleviated by invoking flickering quasar light curves, which would allow for multiple episodes of quasar activity and black hole growth. In this picture the UV emission from the quasar fluctuates as a result of either intrinsic variations in the accretion flow or time-variable obscuration along the line of sight.

If a quasar’s ionizing radiation fades, the intergalactic gas recombines and the neutral gas fraction increases. While the recombination timescale of hydrogen from a highly ionized to a completely neutral state is long, i.e., comparable to the age of the universe, the timescale on which the IGM can recombine from a Ly$\alpha$-transparent highly ionized state of $x_{HI} \sim 10^{-5}$ to an Ly$\alpha$-opaque less ionized state of $x_{HI} \sim 10^{-3}$ is much shorter. Although the size of the proximity zone depends nontrivially on the neutral gas fraction along the line of sight at the limiting optical depth of $\tau_{lim} = 2.3$, corresponding to a 10% flux transmission in the Ly$\alpha$ forest that defines the extent of $R_p$, the time that it takes for the proximity zone of a $z \sim 6$ quasar to disappear after the quasar’s ionizing emission has faded is similarly short, i.e., $\sim 10^4$ yr (see Davies et al. 2020a, for details).

Furthermore, our model is limited to statements about the current luminosity of the quasar, which may not be representative of its average luminosity over the last equilibration timescale. If the quasars were to exhibit extreme variability with magnitude changes of $\sim 1$ mag within $\sim 15$ yr, as observed in some quasars at low redshifts and lower luminosity (e.g., Rumbaugh et al. 2018), our model would not capture these rapid changes appropriately. Moreover, the change in proximity zone size over such short timescales is comparable to the uncertainty on the proximity zone measurement introduced by the redshift estimate, and thus our model is not sensitive to such extreme variability.

However, despite the lack of sensitivity of quasar proximity zones at $z \sim 6$ to extreme variability and potential previous episodes of quasar activity, there are several other indicators that show that flickering quasar light curves, i.e., multiple epochs of black hole growth, cannot account for the complete discrepancy between the estimated short quasar lifetimes and the accretion times required to grow a billion-solar-mass black hole from a stellar remnant black hole seed. For instance, the IGM damping wing feature observed in quasars at $z \gtrsim 7$, where the surrounding intergalactic gas still has a high neutral fraction, allows for an integrated constraint on the total number of emitted ionizing photons, i.e., a measurement of the quasars’ duty cycle. Such measurements around four known $z \gtrsim 7$ quasars have shown that the total time these quasars have been emitting ionizing radiation over the history of the universe is $t_Q \lesssim 10^5$ yr (Davies et al. 2019, 2021, in preparation). Thus, the need for modifications to the standard black hole growth model, such as radiatively inefficient accretion or obscured black hole growth phases, remains even in the presence of flickering quasar light curves.

Additional constraints on flickering quasar light curves and the concomitant growth of SMBHs at $z \sim 6$ can be obtained from the observed distribution of proximity zone sizes. Davies et al. (2020a) model how quasar variability on $\sim 10^5$ yr timescales is imprinted onto the distribution of proximity zone sizes and show that large variations in the ionizing luminosity of quasars on timescales of $\lesssim 10^5$ yr are disfavored based on the good agreement between the bulk of the observed distribution of $R_p$ and the model prediction from light-bulb light curves.

Another argument in favor of light-bulb light curves with $t_Q \sim 10^6$ yr is based on measurements of the proximity zones in the He II Ly$\alpha$ forest. Since the equilibration timescale for He II is longer than for H I, i.e., $\tau_{eq, He II} \sim 3 \times 10^7$ yr, the proximity zones in the He II Ly$\alpha$ forest are sensitive to longer quasar lifetimes and less sensitive to variability on short timescales. Nevertheless, studies of He II Ly$\alpha$ proximity zones provide evidence for a lifetime of $t_Q \sim 10^6$ yr for the quasar population (Khrykin et al. 2019, 2021).

Therefore, it is highly likely that either radiatively inefficient mass accretion rates or dust-enshrouded, UV-obscured black hole growth phases (or a combination of both) are required to explain the rapid assembly of SMBHs (Eilers et al. 2018b; Davies et al. 2019).

7. Summary

We measure the lifetimes of a sample of 10 quasars at $z \sim 6$ based on the extents of their H I proximity zones observed in the rest-frame UV spectra. This sample was preselected out of a parent sample of 122 quasars to show very small proximity zones and thus likely indicate short quasar lifetimes. In Paper I we obtained submillimeter observations for measurements of the quasars’ systemic redshifts, as well as deep optical/NIR spectra to precisely measure the proximity zone sizes for these quasars.

For four quasars in our sample we estimate extremely short lifetimes, i.e., $\log_{10}(t_Q/\text{yr}) < 4$, which increases the known young quasar sample to seven at $5.8 \lesssim z \lesssim 6.3$, including the previously discovered young objects (Eilers et al. 2017a, 2018b; Davies et al. 2020b; Andika et al. 2020). These young quasars contribute 5%–10% of the quasar population at large in Paper I. For the remaining six objects in our sample we measure longer quasar lifetimes of $t_Q \gtrsim 10^7$ yr. Our results are consistent with an average effective quasar lifetime of $t_Q \sim 10^7$ yr for an unbiased, i.e., not preselected toward young ages, ensemble of quasars (e.g., Davies et al. 2019; Khrykin et al. 2016, 2021, K. A. Morey et al. 2021, in preparation), for which one would expect to find newly turned-on quasars $\sim 1$%–10% of the time.
7.1. Future Prospects

In order to explain the rapid growth of SMBHs in the host galaxies of high-redshift quasars, our results provide evidence for radiatively inefficient ($\epsilon \ll 0.1$) mass accretion rates or highly UV-obscured, dust-enshrouded black hole growth phases. In either scenario the onset of the UV-luminous quasar phase in the discovered young objects happened only very recently, i.e., $\lesssim 10^4$ yr before the time of observations, which implies that whatever process triggered the nuclear activity in these objects might still be observable. Thus, the young quasar population represents unique targets to study possible triggering and feedback mechanisms of SMBHs. Future submillimeter observations with high spatial resolution might expose traces of a recent merger or an interaction with a companion galaxy that could have just triggered the nuclear activity in these quasars, or reveal diffuse dust from a recent blowout of enveloping gas and dust layers.

Further progress to distinguish between the different scenarios to explain the growth of SMBHs can be made by combining different techniques to estimate quasar lifetimes. For instance, Integral Field Unit (IFU) observations of the extended emission around quasars with very small proximity zones could provide an additional estimate on the quasars’ lifetimes based on the ionization echo of the emission. If the quasars’ ionizing radiation has been obscured by dust along our line of sight, but the quasars have been accreting matter onto the SMBHs for a much longer time, the ionized regions around the quasars are expected to be extended along unobscured sight lines. On the other hand, the extended ionized nebulae are expected to be small or not at all present if the quasar’s radiation has indeed just turned on recently and radiatively inefficient accretion rates might explain the rapid growth of SMBHs (see Eilers et al. 2018b, for details). Thus, future IFU observations of Ly\(\alpha\) halos or [O\(\text{III}\)] nebulae around young quasars observed, for instance, with the Multi Unit Spectroscopic Explorer (MUSE) on the VLT, NIRSpec IFU on the James Webb Space Telescope (JWST), or the upcoming Large Lenslet Array Magellan Spectrograph (LLAMAS) on the Magellan telescopes will enable us to gain new insights into the timescales of quasar activity and the formation and growth of SMBHs in the early universe.

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Software: numpy (van der Walt et al. 2011), scipy (Virtanen et al. 2020), matplotlib (Hunter 2007), astropy (The Astropy Collaboration et al. 2018).

Appendix

Influence of the Quasars’ Spectral Index

The choice of SED alters the number of emitted ionizing photons. As discussed in Section 4.1, our model assumes a spectral index of $\alpha_\nu = -1.7$ determined by Lusso et al. (2015). In Figure 4 we show the effects of the choice of spectral index by $\pm 0.5$ on our results on the quasar lifetime.

Figure 4. Same as the second row of panels in Figure 1, showing the effects of changing the spectral index of the SED to $\alpha_\nu = -1.2$ (top) and $\alpha_\nu = -2.2$ (bottom) for one exemplary young quasar PSO J158–14.
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