Revealing the Accretion Physics of Supermassive Black Holes at Redshift \( z \sim 7 \) with Chandra and Infrared Observations

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Abstract

X-ray emission from quasars has been detected up to redshift \( z = 7.5 \), although only limited to a few objects at \( z > 6.5 \). In this work, we present new Chandra observations of five \( z > 6.5 \) quasars. By combining with archival Chandra observations of six additional \( z > 6.5 \) quasars, we perform a systematic analysis on the X-ray properties of these earliest accreting supermassive black holes (SMBHs). We measure the black hole masses, bolometric luminosities \( (L_{\text{bol}}) \), Eddington ratios \( (\lambda_{\text{edd}}) \), emission line properties, and infrared luminosities \( (L_{\text{IR}}) \) of these quasars using infrared and submillimeter observations. Correlation analysis indicates that the X-ray bolometric correction (the factor that converts from X-ray luminosity to bolometric luminosity) decreases with increasing \( L_{\text{bol}} \) and that the UV/optical-to-X-ray ratio, \( \lambda_{\text{obs}} \), strongly correlates with \( L_{\text{bol}} \) and moderately correlates with \( \lambda_{\text{edd}} \) and blueshift of CIV emission lines. These correlations are consistent with those found in lower-\( z \) quasars, indicating quasar accretion physics does not evolve with redshift. We also find that \( L_{\text{IR}} \) does not correlate with \( L_{\text{bol}} \) in these luminous distant quasars, suggesting that the ratio of the SMBH growth rate and their host galaxy growth rate in these early luminous quasars are different from those of local galaxies. A joint spectral analysis of the X-ray detected \( z > 6.5 \) quasars yields an average X-ray photon index of \( \Gamma = 2.32^{+0.31}_{-0.30} \), steeper than that of low-\( z \) quasars. By comparing it with the \( \Gamma = \lambda_{\text{edd}} \) relation, we conclude that the steepening of \( \Gamma \) for quasars at \( z > 6.5 \) is mainly driven by their higher Eddington ratios.

Unified Astronomy Thesaurus concepts: Quasars (1319); Early universe (435); X-ray quasars (1821); High-luminosity active galactic nuclei (2034); Supermassive black holes (1663)

1. Introduction

Quasars, the most luminous type of active galactic nuclei (AGN), are believed to be powered by accreting supermassive black holes (SMBHs). The continuum and line emission from luminous quasars, over a large wavelength range, from optical to X-ray, can be characterized by several major components: the optical-ultraviolet (UV) continuum emission, which is explained by a standard accretion disk extending down to the innermost stable circular orbit (ISCO; e.g., Shields 1978), a soft X-ray excess whose origin is still debated (e.g., Arnaud et al. 1985), X-ray emission with a power-law spectrum produced by inverse Compton scattering of photons from the accretion disk of relativistic electrons in the hot corona (e.g., Svensson & Zdziarski 1994), and the broad emission lines emitted from the so-called broad line region (BLR; e.g., Antonucci 1993). Thus the optical/UV to X-ray emission of quasars provide crucial information about the BH mass, the structure and physics of the accretion flow around the central SMBHs.

At present more than 200 quasars have been discovered at redshift \( z > 6 \) (e.g., Fan et al. 2001; Wu et al. 2015; Bañados et al. 2016; Jiang et al. 2016; Reed et al. 2017; Wang et al. 2017; Yang et al. 2017); about 50 quasars have been discovered at \( z > 6.5 \) (e.g., Venemans et al. 2013; Mazzucchelli et al. 2017; Wang et al. 2019b; Yang et al. 2019) and seven at \( z > 7 \) (Mortlock et al. 2011; Bañados et al. 2018; Wang et al. 2018; Matsuoka et al. 2019; Yang et al. 2019, 2020). Extensive optical to near-infrared (NIR) spectroscopic observations of these quasars indicate that billion solar mass SMBHs are already in place when the universe is only ~700 Myr old (Yang et al. 2020). The growth of these early SMBHs is limited by the available accretion time. At \( z \sim 7 \), only \( \sim 14 \) e-folding times elapsed since the first luminous object formed in the universe (i.e., \( z \sim 30 \), Tegmark et al. 1997), corresponding to a factor of \( \sim 10^6 \) increase in mass, placing the most stringent constraints on the SMBH formation and growth mechanisms (e.g., Bañados et al. 2018b; Yang et al. 2020). In order to explain the existence of these SMBHs, many theoretical models have been proposed (see Latif & Ferrara 2016; Inayoshi et al. 2020 and references therein) by invoking either a super-Eddington accretion process...
current understanding of the accretion physics and AGN feedback (e.g., Fabian et al. 2014; Parker et al. 2017). However, X-ray observations are only available for a very limited sample at high redshift. To date, \( \sim 30 \) quasars (e.g., Brandt et al. 2001; Shenmer et al. 2006; Ai et al. 2016, 2017; Nanni et al. 2017, 2018; Connor et al. 2019; Vito et al. 2019) and six quasars at high redshift (Page et al. 2014; Moretti et al. 2014; Bañados et al. 2018a; Vito et al. 2019; Connor et al. 2020; Pons et al. 2020) have been detected in X-ray with Chandra and XMM-Newton. Two key findings have been established based on these limited X-ray observations:

First, there is a tight correlation between the optical/UV–X-ray luminosity ratio (\( \alpha_{\text{ox}} \)) and the UV luminosity (i.e., \( L_{2500} \)), and it does not evolve from low redshift up to \( z \sim 6 \) (e.g., Just et al. 2007; Lusso & Risaliti 2016; Nanni et al. 2017). Recent investigations of several \( z \gg 6.5 \) quasars (Moretti et al. 2014; Page et al. 2014; Bañados et al. 2018b; Vito et al. 2019) suggest that this relation might still hold in the epoch of reionization. Since \( \alpha_{\text{ox}} \) measures the relative importance of the hot corona versus the accretion disk, the steeper \( \alpha_{\text{ox}} \) in higher luminosity quasars indicates the dominance of the disk emission with respect to the hot electron corona emission in luminous quasars (see Brandt & Alexander 2015 for a review).

The other key finding is that there is a moderate positive correlation between the photon index, \( \Gamma \), of the hard X-ray spectrum (\( N(E) \propto E^{-\Gamma} \)) and the Eddington ratio (\( \lambda_{\text{Edd}} = L/LEdd \)) established from a sizable sample of sources up to \( z \sim 3 \), with larger \( \Gamma \) corresponding to higher \( \lambda_{\text{Edd}} \) (e.g., Shenmer et al. 2008; Brightman et al. 2013, but see Trakhtenbrot et al. 2017). A high accretion rate is expected to increase the disk temperature and thus the level of disk emission, resulting in the increase of Compton cooling of the corona (e.g., Maraschi & Haardt 1997), and producing a steep (large \( \Gamma \)) X-ray spectrum. However, the relation between \( \Gamma \) and \( \lambda_{\text{Edd}} \) is far from well established for the most distant quasars. Measuring \( \Gamma \) is extremely difficult at high redshift because of the limited photon statistics. To date, only for four quasars (three at \( z \sim 6 \) quasars and one at \( z > 7 \)) have more than 100 X-ray photons been detected, which is required to place reasonable constraints on \( \Gamma \) for individual quasars (Moretti et al. 2014; Page et al. 2014; Ai et al. 2017; Nanni et al. 2017, 2018). Alternatively, stacking studies of quasars to study the average \( \Gamma \) at different redshifts indicates that the average \( \Gamma \) does not evolve from \( z \sim 0 \) to \( z \sim 6 \) (Vignali et al. 2005; Shenmer et al. 2006; Just et al. 2007; Nanni et al. 2017). However, the more recent work by Vito et al. (2019) indicates that the average \( \Gamma \) of three \( z > 6.5 \) quasars is slightly steeper than but still consistent with those of typical quasars at \( z < 6 \).

In this paper, we report new Chandra observations of five quasars at \( z > 6.5 \), significantly increasing the number of X-ray observed quasars at these redshifts. Together with archival Chandra observations of six additional \( z > 6.5 \) quasars, we perform joint spectral fitting of all X-ray detected \( z \gg 6.5 \) quasars with a mean quasar redshift of \( z = 6.822 \). We also analyze the NIR spectra for these quasars and investigate the relations between quasar rest-frame UV and X-ray properties. In Section 2 we describe the X-ray and NIR observations and data reduction. We present the X-ray fluxes, luminosities, \( \alpha_{\text{ox}} \), and measurements from Chandra observations, the black hole masses, bolometric luminosities, Eddington ratios and line properties measurements from NIR spectral fitting, and the infrared luminosities measured from submillimeter observations in Section 3. The correlation between X-ray and other properties of individual quasars are investigated in Section 4. We present the stacked X-ray spectrum, joint spectral fitting, and the mean properties of these \( z > 6.5 \) quasars in Section 5. Finally, we conclude and summarize our findings in Section 6. Throughout the paper, we adopt a flat cosmological model with \( H_0 = 68.5 \text{ km s}^{-1} \text{Mpc}^{-1} \) (Betoule et al. 2014), \( \Omega_M = 0.3 \), and \( \Omega_L = 0.7 \). All the uncertainties of our measurements reported in this work are at the 1\( \sigma \) confidence level, while upper limits are reported at the 95% confidence level.

### 2. Observations and Data Reduction

#### 2.1. Chandra X-Ray Observations

We obtained Chandra observations of five quasars at \( z > 6.5 \) using the Advanced CCD Imaging Spectrometer (ACIS-S; Garmire et al. 2003) instrument in Cycle 19 (proposal number: 19700283, PI. Fan). The five quasars observed were J002429.77 +391319.0 (hereafter J0024+3913), Tang et al. (2017) at \( z = 6.6210, J022426.54–471129.4 \) (hereafter J0224–4711, Reed et al. 2017) at \( z = 6.5223, J104819.09–010940.21 \) (hereafter J1048–0109, Wang et al. 2017) at \( z = 6.6759, J123233.19 +121755.3 \) (hereafter J1232+1217, Mazzucchelli et al. 2017) at \( z = 6.5850, J234833.34–305410.0 \) (hereafter J2348–3054, Venemans et al. 2013) at \( z = 6.9018 \). These targets were positioned on the ACIS-S3 chip with the Very Faint telemetry format and the Timed Exposure mode. The observation log and the basic properties (i.e., redshift and brightness) of these quasars are listed in Table 1.

In order to increase the sample size of our analysis we also include the six other \( z > 6.5 \) quasars that were observed by Chandra and archived as of 2020 April. Specifically, J112001.48+064124.3 (hereafter J1120+0641, Mortlock et al. 2011) at \( z = 7.09 \) was observed in Cycle 12 (Page et al. 2014), J134208.10+092838.6 (hereafter J1342+0928, Bañados et al. 2018a) at \( z = 7.54 \) was observed in Cycle 18 (Bañados et al. 2018b), and four other quasars were observed in Cycle 19 (Vito et al. 2019). The observation log and properties of these quasars are also listed in Table 1. The Galactic H1 column density at each quasar position calculated from Kalberla et al. (2005) is also listed in Table 1. Similar to our new observations, these \( z > 6.5 \) quasars were positioned on the ACIS-S3 chip with the Timed Exposure mode. J1120+0641 was observed with the Faint telemetry format and all other quasars were observed with the Very Faint mode.

The data were reprocessed with the chandra_repro script in the standard Chandra’s data analysis system: CIAO (Fruscione et al. 2006) version 4.12 and CALDB version 4.9.0. In the analyses, only grade 0, 2, 3, 4, and 6 events were used. In the process, we set the option check_vf_phi=\text{yes} in the case of observations taken in the very faint mode. The exposure maps and the PSF maps were created with the fluximage script and the mkpsfmap script, respectively. Considering the increasingly uncertain quantum efficiency of ACIS at lower energies and the steeply increasing background at higher energies, we only used the X-ray counts at observed frame energies of 0.5–7 keV, following Nanni et al. (2017). In order to detect sources we first performed source detections...
| Name       | R.A.           | Decl.          | $z$     | $J_{AB}$       | Obs. date | ObsID | Mode   | $t_{exp,X}$ (ks) | $t_{exp,NIR}$ (ks) | $N_H$ ($10^{20}$ cm$^{-2}$) | Ref. (disc./$z$) |
|------------|----------------|----------------|---------|----------------|-----------|-------|--------|-----------------|-----------------|----------------------|------------------|
| J2348−3054 | 23:48:33.34    | −30:54:10.0    | 6.9018  | 21.11 ± 0.11  | 2018-09-04| 20414 | VFAINT | 42.50           | 20416           | 1.30                 | V13/V16          |
| J1048−0109 | 10:48:19.09    | −01:09:40.2    | 6.6759  | 20.61 ± 0.17  | 2019-01-28| 20415 | VFAINT | 34.76           | 20416           | 3.60                 | W17/D18          |
| J0024+3913 | 00:24:29.77    | +39:13:19.0    | 6.6210  | 20.70 ± 0.15  | 2018-05-21| 20416 | VFAINT | 19.70           | 20417           | 6.76                 | T17/M17          |
| J2132+1217 | 21:32:33.19    | +12:17:55.3    | 6.5850  | 19.55 ± 0.11  | 2018-08-20| 20417 | VFAINT | 17.82           | 20418           | 4.8                  | M17/D18          |
| J0224−4711 | 02:24:26.54    | −47:11:29.4    | 6.5223  | 19.73 ± 0.06  | 2018-03-05| 20418 | VFAINT | 17.72           | 20419           | 1.66                 | R17/W20          |
| J1342+0928 | 13:42:08.11    | +09:28:38.6    | 7.5413  | 20.36 ± 0.10  | 2017-12-15| 20124 | VFAINT | 24.73           | 20125           | 2.04                 | B18/V17          |
| J1120−0641 | 11:20:01.48    | +06:41:24.3    | 7.0842  | 20.30 ± 0.15  | 2011-02-04| 13203 | FAINT  | 15.84           | 20113           | 5.07                 | M11/D18          |
| J2232+2930 | 22:32:55.15    | +29:30:32.0    | 6.6580  | 20.28 ± 0.14  | 2018-01-30| 20395 | VFAINT | 54.21           | 20396           | 6.71                 | V15/D18          |
| J0305−3150 | 03:05:16.92    | −31:50:56.0    | 6.6145  | 20.70 ± 0.09  | 2018-05-11| 20394 | VFAINT | 49.88           | 20395           | 1.42                 | V13/V16          |
| J0226+0302 | 02:26:01.87    | +03:02:59.3    | 6.5412  | 19.43 ± 0.10  | 2018-10-09| 20390 | VFAINT | 25.90           | 20391           | 3.04                 | V15/B15          |
| J1110−1329 | 11:10:33.96    | −13:29:45.6    | 6.5148  | 21.16 ± 0.09  | 2018-02-20| 20397 | VFAINT | 59.33           | 20398           | 5.31                 | V15/D18          |

Note. The first section includes five quasars with new Chandra observations, while the second section represents six quasars with archival X-ray observations. All redshift comes from the fitting of the [C II] emission line. The sources are sorted by decreasing redshift.

References. B15: Bañados et al. (2015); B18: Bañados et al. (2018a); D18: Decarli et al. (2018); M17: Mazzucchelli et al. (2017); R17: Reed et al. (2017); T17: Tang et al. (2017); V13: Venemans et al. (2013); V16: Venemans et al. (2016); W20: The [C II] redshift of this object is obtained from ALMA Cycle 6 observations (2018.1.01188.S, PI: Wang) (F. Wang et al. 2021, in preparation).
Table 2
X-Ray Photometry and Quasar X-Ray Properties

| Name            | Net Counts | HR  | Flux$^b$ | $L_x$-10$^{22}$ keV | $\alpha_{ox}$ |
|-----------------|------------|-----|----------|---------------------|---------------|
|                 | 0.5–7.0 keV | 0.5–2.0 keV | 2.0–7.0 keV | 0.5–7.0 keV | 0.5–2.0 keV | 2.0–7.0 keV | 10$^{44}$ erg s$^{-1}$ |          |
| J1342+0928      | 14.0$^{+2.0}_{-1.0}$ | 10.2$^{+1.0}_{-1.0}$ | 3.8$^{+1.2}_{-1.2}$ | -0.46$^{+0.29}_{-0.29}$ | 2.97$^{+0.85}_{-1.06}$ | 1.56$^{+0.33}_{-0.50}$ | 1.41$^{+0.40}_{-0.34}$ | 12.80$^{+3.69}_{-1.61}$ | -0.05 |
| J1120+0641      | 5.3$^{+1.6}_{-1.4}$ | 4.2$^{+1.0}_{-1.0}$ | 1.6$^{+1.3}_{-1.3}$ | -0.37$^{+0.34}_{-0.57}$ | 2.89$^{+1.56}_{-2.01}$ | 1.20$^{+0.35}_{-0.62}$ | 1.09$^{+0.40}_{-0.34}$ | 8.52$^{+1.52}_{-1.66}$ | 0.05 |
| J2348–3054      | <8.6$^a$ | <3.0 | <9.7 | <2.6 | <1.19 | <1.07 | <7.96 | <1.56 |
| J0488–0109      | <4.7 | <4.1 | <4.0 | <1.54 | <0.81 | <0.73 | <5.02 | <1.72 |
| J2202+2930      | 6.6$^{+1.1}_{-1.0}$ | 6.3$^{+0.8}_{-1.0}$ | 0.4$^{+1.3}_{-1.0}$ | -0.73$^{+0.07}_{-0.27}$ | 1.45$^{+0.66}_{-0.47}$ | 0.76$^{+0.33}_{-0.43}$ | 0.69$^{+0.30}_{-0.30}$ | 4.68$^{+1.93}_{-1.73}$ | -0.09 |
| J0004+3913      | <8.2 | <5.9 | <5.6 | <4.93 | <2.59 | <2.34 | <15.74 | <1.47 |
| J0305–3150      | <5.8 | <4.2 | <5.1 | <1.31 | <0.69 | <0.62 | <8.18 | <1.73 |
| J1218–1217      | 15.0$^{+2.1}_{-2.0}$ | 7.5$^{+1.3}_{-1.2}$ | 7.5$^{+1.9}_{-1.9}$ | 0.00$^{+0.27}_{-0.27}$ | 9.93$^{+1.38}_{-2.85}$ | 5.22$^{+1.77}_{-1.99}$ | 4.71$^{+1.46}_{-1.25}$ | 31.32$^{+1.02}_{-1.50}$ | 0.05 |
| J0226–0302      | 5.0$^{+1.6}_{-1.4}$ | 3.7$^{+1.3}_{-1.4}$ | 1.2$^{+1.5}_{-1.6}$ | -0.49$^{+0.19}_{-0.51}$ | 2.18$^{+1.37}_{-2.08}$ | 1.14$^{+0.82}_{-0.55}$ | 1.03$^{+0.49}_{-0.49}$ | 6.73$^{+1.65}_{-1.81}$ | -0.11 |
| J0244–4711      | 18.1$^{+3.4}_{-3.0}$ | 15.7$^{+1.5}_{-1.4}$ | 2.4$^{+1.9}_{-1.8}$ | -0.72$^{+0.52}_{-0.31}$ | 11.44$^{+2.41}_{-2.72}$ | 6.01$^{+1.79}_{-1.43}$ | 5.43$^{+1.62}_{-1.26}$ | 35.26$^{+10.39}_{-1.55}$ | 0.04 |
| J1110–1329      | <8.0 | <3.0 | <8.8 | <1.58 | <0.83 | <0.75 | <4.86 | <1.60 |

Notes. The sources are sorted by decreasing redshift. The last column, $\alpha_{ox}$, is measured using Equation (2) and the $L_{2500}$ are listed in Table 3. The $\Delta \alpha_{ox}$ used in Figure 5 can be derived by subtracting $\alpha_{ox}$ from the $\alpha_{ox}$-$L_{2500}$ relation in Timlin et al. (2020).

$^a$ For undetected objects, we report the upper limit corresponding to the 95% confidence interval.

$^b$ The Galactic absorption-corrected X-ray flux in the observed band in units of 10$^{-13}$ erg cm$^{-2}$ s$^{-1}$.

![Image of cutouts](image.png)

**Figure 1.** Full-band (0.5–7 keV) Chandra cutouts of the 11 $z > 6.5$ quasars. The images are centered at the optical positions listed in Table 1. The images have been smoothed with a 1 pixel Gaussian kernel. Red solid circles highlight targets detected by wavdetect, while the orange dashed circles denote targets not detected by wavdetect. All circles represent our extraction regions with a 3" radius. All cutouts are in the size of 20" $\times$ 20".
centered at the optical positions with an inner radius of 10\('0\) and an outer radius of 30\('0\). The net X-ray counts detected in the soft band (0.5–2 keV), the hard band (2–7 keV), and the full band (0.5–7 keV) within the 30\('0\) radius circular region are reported in Table 2. For undetected sources we report the 2\(\sigma\) upper limits (corresponding to the 95\% confidence intervals) computed from the srcflux script in CIAO. Table 2 also lists the hardness ratio HR = (\(H - S\))/(\(H + S\)), where H and S are the net counts in the hard (2–7 keV) and soft (0.5–2 keV) bands, respectively. The HR for those Chandra detected quasars are estimated with the Bayesian method described by Park et al. (2006). The full band (0.5-7 keV) image stamps are shown in Figure 1.

2.2. Near-infrared Spectroscopy

We note that most of the quasars investigated here have BH mass estimates in the literature (Mortlock et al. 2011; De Rosa et al. 2014; Mazzucchelli et al. 2017; Bahados et al. 2018a; Tang et al. 2019; Onoue et al. 2020; Schindler et al. 2020). However, these estimates were based on different fitting algorithms and different single-epoch virial scaling relations. To reduce the biases introduced by different methods we perform our own self-consistent measurements of the masses and Eddington ratios of these SMBHs. We reduced and analyzed the archival NIR spectroscopic observations of these quasars. The quasars J1342+0928, J1120+0641, J0024+3913, and J2232+2930 were observed with Gemini/GNIRS (Elias et al. 2006a, 2006b) using the Cross-dispersed mode. J1110–1329 was observed with Magellan/FIRE (Simcoe et al. 2010) using the Echelle mode. All the other quasars presented in this work were observed with VLT/X-Shooter (Vernet et al. 2011).

We reduced both GNIRS and X-Shooter spectra with the newly developed open source spectroscopic data reduction pipeline PypeIt\(^{15}\) (Prochaska et al. 2020a, 2020b). The wavelength solutions were derived from the night sky OH lines in the vacuum frame. The sky background was subtracted with the standard A–B mode and then a b-spline fitting procedure was performed to further clean up the sky line residuals following Bochanski et al. (2009). An optimal extraction (Horne 1986) is then performed to generate 1D science spectra. We flux the extracted spectra with sensitivity functions derived from standard star observations. We then stacked the fluxed individual exposures and individual orders. The telluric corrections are performed by jointly fitting the atmospheric models derived from the Line-By-Line Radiative Transfer Model (LBLRTM\(^{16}\); Clough et al. 2005) and a quasar model based on a Principal Component Analysis method (Davies et al. 2018) to the stacked quasar spectra. We then scaled the telluric corrected spectra to match the J-band photometry of each object by carrying out synthetic photometry on the spectrum for the purpose of absolute flux calibration. Finally, we corrected the Galactic extinction based on the dust map (Schlegel et al. 1998) and extinction law (Cardelli et al. 1989). The fully calibrated NIR spectra of these quasars are shown in Figure 2. The FIRE spectrum was reduced with the standard FIREHOSE pipeline, which evolved from the MASE pipeline for optical échelle reduction (Bochanski et al. 2009). We corrected for telluric absorption features by obtaining a spectrum of an A0V star at a comparable observing time.

3. Measurements and Results

Since all quasars have less than 20 net counts in the full 0.5–7.0 keV band, we do not attempt spectral fitting for individual quasars. We measure the X-ray flux by assuming a power-law spectrum with \(\Gamma = 2.0\) (typical of luminous quasars, e.g., Nanni et al. 2017; Vito et al. 2019), accounting for the Galactic absorption (Kalberla et al. 2005), and using the response matrices and ancillary files extracted at the position of each target. The rest-frame 2–10 keV luminosities were estimated by assuming \(\Gamma = 2.0\) as listed in Table 2. The measured X-ray luminosity of these quasars spans more than an order of magnitude with \(L_{2-10\, \text{keV}} \lesssim 4 \times 10^{44} \text{ erg s}^{-1}\). Note that the \(L_{2-10\, \text{keV}}\) would be \(\sim 20\%\) higher if we use \(\Gamma = 2.3\), the average photon index of \(z > 6.5\) quasars derived from Section 5. Considering that most previous work has used \(\Gamma \approx 2\) when measuring \(L_{2-10\, \text{keV}}\) at high redshifts (e.g., Nanni et al. 2017; Vito et al. 2019), we will only use the \(L_{2-10\, \text{keV}}\) values derived by assuming \(\Gamma = 2\) in what follows.

To derive the rest-frame ultraviolet (UV) luminosities, black hole masses, and Eddington ratios for these quasars we performed a global spectral fitting on the de-redshifted NIR spectra following Wang et al. (2020). Briefly, we first fit a pseudo-continuum model to the emission line (except for iron emission) free regions. The pseudo-continuum model includes three components, a power-law continuum \(f_{\lambda} \propto \lambda^{\Gamma}\), Balmer continuum (e.g., De Rosa et al. 2014), and iron emission (Vestergaard & Wilkes 2001; Tsuzuki et al. 2006). The iron template was constructed by composing the iron emission from Tsuzuki et al. (2006) (2200–3500 Å) and Vestergaard & Wilkes (2001) (1100–2200 Å). The Mg II and C IV lines are then fitted with two Gaussian functions for each line after subtracting the pseudo-continuum model. We perform the whole fitting process iteratively and broaden the iron template by convolving it with a Gaussian kernel to match the line width of the Mg II line. Following Wang et al. (2020), we use a Monte Carlo approach to estimate the spectral measurement uncertainties. We created 100 mock spectra by randomly adding Gaussian noise to each pixel with standard deviation equal to the spectral error at that pixel. Then we applied exactly the same fitting procedure to these mock spectra. The uncertainties of measured spectral properties are then estimated as the average of the 16\% and 84\% percentile deviation from the median.

The derived power-law continuum slopes (\(\alpha_{\lambda}\)), continuum luminosities at rest-frame 2500 Å, line widths, and redshifts are given in Table 3. The Mg II and C IV redshifts listed in Table 3 were estimated based on the peak of the Gaussian fitting of each line. The redshifts based on the Mg II line are generally consistent with \(< 800 \text{ km s}^{-1}\) the [C II] redshifts listed in Table 1. The C IV lines of all the quasars exhibit large blueshifts relative to both [C II] and Mg II lines, which we discuss in detail in Section 4.2. The bolometric luminosities are estimated by assuming a bolometric correction of \(L_{\text{bol}} = 5.15 \times L_{3000\, \text{Å}}\) (Shen et al. 2011). The black hole masses, \(M_{\text{BH}}\), are then estimated using the single viral estimator proposed by

\(^{15}\) https://github.com/pypeit/PypeIt

\(^{16}\) http://rtweb.aer.com/lblrtm.html
The Eddington ratio of each quasar is then calculated as 
\[ \lambda_{\text{Edd}} = \frac{L_{\text{bol}}}{L_{\text{Edd}}} \]
where the \( L_{\text{Edd}} = 1.26 \times 10^{38} M_{\odot} \) is the Eddington luminosity. The \( M_{\odot} \) and \( \lambda_{\text{Edd}} \) are listed in Table 3. Note that the quoted uncertainties of \( M_{\odot} \) and \( \lambda_{\text{Edd}} \) do not
### Table 3
Quasar Properties Derived from Near-infrared and Submillimeter Observations

| Name       | $M_{1450}$ | $z_{\text{Mg II}}$ | $z_{\text{C IV}}$ | FWHM$_{\text{Mg II}}$ km s$^{-1}$ | FWHM$_{\text{C IV}}$ km s$^{-1}$ | $\lambda L_{2500}$ | $L_{\text{bol}}$ 10$^{46}$ erg s$^{-1}$ | $M_{\text{BH}}$ 10$^9$ $M_{\odot}$ | $\lambda_{\text{Hd}}$ | $\alpha_{\lambda}$ | $S_{\text{1 mm}}$ mJy | $L_{\text{IR}}$ 10$^{46}$ erg s$^{-1}$ | Ref. ($S_{\text{1 mm}}$) |
|------------|------------|--------------------|-------------------|----------------------------------|-------------------------------|-------------------|--------------------------------|-----------------------------|----------------|----------------|----------------|--------------------------------|----------------|-----|
| J1142+0928 | 26.65      | 7.531 ± 0.004      | 7.361 ± 0.025     | 2680 ± 255                       | 11776 ± 1102                  | 3.40 ± 0.23        | 1.42 ± 0.12                       | 0.86 ± 0.20                  | 1.26 ± 0.16      | −1.54 ± 0.04 | 0.41 ± 0.07 | 0.57 ± 0.10                        | V18           |
| J1120+0641 | 26.45      | 7.095 ± 0.002      | 7.027 ± 0.005     | 3454 ± 66                        | 7554 ± 690                    | 2.80 ± 0.24        | 1.35 ± 0.11                       | 1.40 ± 0.10                  | 0.74 ± 0.06      | −1.36 ± 0.02 | 0.53 ± 0.04 | 0.73 ± 0.06                        | V18           |
| J2348−3054 | 25.84      | 6.887 ± 0.005      | 6.866 ± 0.001     | 4385 ± 786                       | 4264 ± 625                    | 1.45 ± 0.17        | 0.68 ± 0.09                       | 1.60 ± 0.69                  | 0.33 ± 0.11      | −1.55 ± 0.18 | 1.92 ± 0.14 | 2.64 ± 0.19                        | V18           |
| J1048−0109 | 26.03      | 6.661 ± 0.005      | 6.603 ± 0.015     | 2676 ± 1240                      | 10202 ± 536                   | 2.34 ± 0.28        | 1.21 ± 0.12                       | 0.79 ± 0.58                  | 1.17 ± 0.37      | −0.99 ± 0.09 | 2.84 ± 0.04 | 3.90 ± 0.05                        | D18           |
| J2232+2930 | 26.34      | 6.666 ± 0.007      | 6.642 ± 0.001     | 5234 ± 321                       | 3938 ± 215                    | 2.35 ± 0.40        | 1.11 ± 0.19                       | 2.91 ± 0.57                  | 0.29 ± 0.02      | −1.49 ± 0.02 | 0.97 ± 0.22 | 1.33 ± 0.30                        | V18           |
| J0024+3913 | 25.62      | 6.618 ± 0.001      | 6.613 ± 0.001     | 1711 ± 139                       | 2441 ± 5                      | 1.64 ± 0.21        | 0.85 ± 0.10                       | 0.27 ± 0.04                  | 2.40 ± 0.38      | −0.94 ± 0.05 | 0.55 ± 0.18 | 0.76 ± 0.25                        | V18           |
| J0305+3150 | 26.11      | 6.608 ± 0.002      | 6.576 ± 0.003     | 2617 ± 609                       | 5624 ± 300                    | 2.08 ± 0.13        | 1.01 ± 0.07                       | 0.70 ± 0.38                  | 1.12 ± 0.44      | −1.32 ± 0.03 | 3.29 ± 0.10 | 4.52 ± 0.14                        | V18           |
| J2132+1217 | 27.08      | 6.588 ± 0.001      | 6.578 ± 0.001     | 2146 ± 263                       | 3063 ± 22                     | 3.97 ± 0.21        | 1.77 ± 0.09                       | 0.62 ± 0.17                  | 2.20 ± 0.50      | −1.78 ± 0.01 | 0.47 ± 0.15 | 0.65 ± 0.21                        | V18           |
| J0226+0302 | 27.26      | 6.532 ± 0.017      | 6.427 ± 0.003     | 3713 ± 289                       | 9346 ± 1298                   | 5.36 ± 0.27        | 2.50 ± 0.13                       | 2.20 ± 0.39                  | 0.87 ± 0.10      | −1.54 ± 0.01 | 2.50 ± 0.50 | 3.44 ± 0.09                        | V18           |
| J0224+4711 | 26.67      | 6.527 ± 0.001      | 6.486 ± 0.001     | 2655 ± 144                       | 5760 ± 96                     | 5.85 ± 0.35        | 3.36 ± 0.20                       | 1.30 ± 0.18                  | 1.98 ± 0.15      | −0.39 ± 0.01 | 1.96 ± 0.07 | 2.70 ± 0.10                        | W20           |
| J1110−1329 | 25.35      | 6.511 ± 0.004      | 6.465 ± 0.020     | 2267 ± 352                       | 13778 ± 4155                  | 1.10 ± 0.14        | 0.55 ± 0.06                       | 0.38 ± 0.14                  | 1.10 ± 0.24      | −1.21 ± 0.06 | 0.87 ± 0.05 | 1.20 ± 0.07                        | D18           |

**Note.** The sources are sorted by decreasing redshift.

**References.** D18: Decarli et al. (2018); V18: Venemans et al. (2018); W20: The 1mm continuum flux density of this object is obtained from ALMA Cycle 6 observations (2018.1.01188.S, PI: Wang) (F. Wang et al. 2021, in preparation).
include the systematic uncertainties in the scaling relation, which is 0.55 dex (Vestergaard & Osmer 2009).

With the X-ray and UV luminosity, we can then measure the optical-X-ray power-law slope, which is defined as

$$\alpha_{\text{ox}} = \frac{\log(f_{2\text{ keV}}/f_{2500 \AA})}{\log(\nu_{2\text{ keV}}/\nu_{2500 \AA})},$$

(2)

where $f_{2\text{ keV}}$ and $f_{2500 \AA}$ are the flux densities at rest-frame 2 keV and 2500 Å, respectively. The computed $\alpha_{\text{ox}}$ values are listed in Table 2.

In order to measure the infrared luminosities of these quasars we used the 1mm (in the observed frame) ALMA observations collected by Venemans et al. (2018) and Decarli et al. (2018). In addition, we observed one quasar in our sample, J0224–4711, with ALMA in Cycle 6 (2018.1.01188.S, PI: Wang). In this paper, we only use the [CII] based redshift (Table 1) and the 1mm continuum (Table 3) measurements, while the detailed data reduction of our ALMA observations will be presented elsewhere (F. Wang et al. 2021, in preparation). Since Haro 11, a low metallicity dwarf galaxy, has been suggested as the best candidate analog for high-$z$ quasar host galaxies (e.g., Lyu et al. 2016), we estimate the 8–1000 μm infrared luminosities ($L_{\text{IR}}$) of these quasar host galaxies by scaling the observed 1mm continuum to the Haro 11 spectral energy distribution (SED). The estimated $L_{\text{IR}}$ are listed in Table 3. The star formation rate (SFR) can be calculated as

$$\text{SFR}(M_\odot \text{ yr}^{-1}) = 5.0 \times 10^{-44} L_{\text{IR, erg s}^{-1}},$$

(Lyu et al. 2016). Note that the $L_{\text{IR}}$ estimated using the Haro 11 template is usually about two times higher than that estimated from a modified blackbody with $T = 47$ K and $\beta = 1.6$ (Beelen et al. 2006), because the modified blackbody misses flux in the mid-infrared.

4. Correlations between X-Ray Emission and Other Properties of Individual Quasars

In this section, we investigate the relationships between X-ray emission and other properties of these high redshift quasars. Since our quasar sample is relatively small and only occupies the bright end (i.e., $L_{\text{bol}} \gtrsim 5 \times 10^{46}$ erg s$^{-1}$) of the quasar population at very high redshift, we consider a sample of ∼2000 SDSS quasars at $1.7 \leq z \leq 2.7$ that have Chandra observations (Timlin et al. 2020) to expand both sample size, luminosity range, and redshift range. We further restrict the redshift to be $z \geq 2.0$ to ensure that we have the same rest-frame UV spectral coverage as the $z > 6.5$ quasars studied here; this results in a sample of 1175 objects. We then perform exactly the same spectral fitting method used in Section 3 to compute the UV luminosities, $L_{\text{bol}}$, BH masses, and Eddington ratios of these lower redshift quasars. We successfully fit the Mg II emission lines in 897 of 1175 objects, as some SDSS spectra have very low quality, some are strongly affected by residuals from OH sky lines, and some were obtained from the earlier SDSS spectrograph, which does not fully cover the wavelength range.

The $L_{2-10 \text{ keV}}$ of these SDSS quasars are adopted from Timlin et al. (2020) and converted to the cosmological model used in this paper. The $\alpha_{\text{ox}}$ are then calculated using $f_{2500 \AA}$ from our spectra fitting and $f_{2 \text{ keV}}$ from Timlin et al. (2020). In order to determine the $L_{\text{IR}}$ and SFR of SDSS quasars, we cross-matched the SDSS quasars from Timlin et al. (2020) with the Herschel/SPIRE Point Source Catalogue (SPSC17). To maximize the number of objects having both X-ray and Herschel observations, we used the full sample of ∼2000 quasars from Timlin et al. (2020) for the matching. There are ∼400 quasars within the Herschel/SPIRE pointings but only 61 (∼15%) have been detected in at least one of the three bands (250, 350, and 500 μm). Thus, the 61 quasars only represent the far-infrared bright quasar population limited by the shallow Herschel observations. The $L_{\text{IR}}$ of these SDSS quasars were then measured by fitting the SPIRE photometry to the Haro 11 SED, similar to the method used for $z > 6.5$ quasars. We also collected the 1mm observations for X-ray detected 6 < $z < 6.5$ quasars (Vito et al. 2019) from Venemans et al. (2018) and Decarli et al. (2018) and then measured the $L_{\text{IR}}$ and SFR of these 6 < $z < 6.5$ quasars using the same method for the $z > 6.5$ quasars.

4.1. X-Ray Bolometric Correction

Determining the relationship between X-ray luminosity and bolometric luminosity is crucial in estimating the AGN bolometric luminosity function (e.g., Hopkins et al. 2007) and the mass function of SMBH (e.g., Marconi et al. 2004). The relation between $L_{2-10 \text{ keV}}$ and $L_{\text{bol}}$ has been well studied and an increasing bolometric correction $k_{\text{bol}} = L_{\text{bol}}/L_{2-10 \text{ keV}}$ with bolometric luminosity has been suggested (e.g., Marconi et al. 2004; Hopkins et al. 2007; Martocchia et al. 2017). In Figure 3, we show the relation between $L_{2-10 \text{ keV}}$ and $L_{\text{bol}}$ of 11 $z > 6.5$ quasars, 16 $6 < z < 6.5$ quasars from Vito et al. (2019) as well as 897 SDSS $z \sim 2$ quasars. The $k_{\text{bol}}$ of most SDSS $z \sim 2$ quasars are in the range of $10 \lesssim k_{\text{bol}} \lesssim 100$, with the most luminous ones at $k_{\text{bol}} \sim 100$. The 11 $z > 6.5$ quasars have a bolometric luminosity range of $0.5–3.4 \times 10^{45}$ erg s$^{-1}$, and an X-ray luminosity range of $0.5–3.5 \times 10^{45}$ erg s$^{-1}$.

\footnote{https://doi.org/10.5270/csa-6g/kpzh}
directly measured from quasar spectra. This plot indicates that there is no
\( \alpha \) have been corrected to the cosmology adopted in this work. The
relation does not depend on redshift.

Figure 4. The \( \alpha \) vs. \( L_{2500\AA} \) plot. All symbols have the same meaning as in
Figure 3, except that we also include quasars at \( 5.5 < z < 6.9 \) from Nanni et al. (2017) as indicated by open triangles. All data points from the literature have been corrected to the cosmology adopted in this work. The \( L_{2500\AA} \) collected from the literature were estimated from the \( M_{1450\AA} \) by assuming a power-law slope of \( \alpha_p = -0.5 \), while the \( L_{2500\AA} \) for \( z > 6.5 \) quasars are directly measured from quasar spectra. This plot indicates that there is no redshift evolution of the \( \alpha_{ox} - L_{2500\AA} \) relation.

4.2. Optical/UV to X-Ray Flux Ratio, \( \alpha_{ox} \)

The \( \alpha_{ox} \) measurement traces the relative importance of the disk emission versus corona emission and is an important parameter for investigating the accretion physics of luminous quasars (e.g., Brandt & Alexander 2015). Previous studies have shown that there is a tight correlation between \( \alpha_{ox} \) and \( L_{2500\AA} \) (e.g., Just et al. 2007; Lusso & Risaliti 2016). Nanni et al. (2017) and Vito et al. (2019) recently used more measurements of high-redshift quasars and showed that the \( \alpha_{ox} - L_{2500\AA} \) relation does not depend on redshift.

We further investigate the \( \alpha_{ox} - L_{2500\AA} \) relationship of high-redshift quasars in three redshift bins with \( 5.5 < z < 6.0 \) quasars from Nanni et al. (2017), \( 6.0 < z < 6.5 \) quasars from Vito et al. (2019), and \( z > 6.5 \) quasars from our analysis, which are shown in Figure 4. In this Figure, we also plot \( \alpha_{ox} - L_{2500\AA} \) measured by fitting lower redshift quasars (Just et al. 2007; Martocchia et al. 2017; Timlin et al. 2020) as well as from \( z > 6 \) quasars (Nanni et al. 2017). Our analysis agrees with previous work (e.g., Nanni et al. 2017; Bañados et al. 2018b; Vito et al. 2019) showing a tight \( \alpha_{ox} - L_{2500\AA} \) relation for quasars at different redshifts. In Figure 5, we show the relation between \( \Delta \alpha_{ox} \), the difference between the measured \( \alpha_{ox} \) and the value expected from the Timlin et al. (2020) \( \alpha_{ox} - L_{2500\AA} \) relation, and quasar redshift. At all redshifts, the \( \Delta \alpha_{ox} \) is distributed around zero, indicating that there is no redshift evolution of the \( \alpha_{ox} - L_{2500\AA} \) relationship up to \( z \sim 7 \). Since \( L_{2500\AA} \) is proportional to \( L_{bol} \) (because the \( L_{bol} \) was estimated from \( L_{3000\lambda} \)), and \( \alpha_{ox} \) is a relation between \( L_{2500\AA} \) and X-ray luminosity, the lack of redshift evolution of the \( \alpha_{ox} - L_{2500\AA} \) relation is fully consistent with the discussion in

Figure 5. The \( \Delta \alpha_{ox} \) vs. redshift plot. All symbols have the same meaning as in
Figure 4.

Figure 6. The correlation between \( \alpha_{ox} \) and Eddington ratio, \( \lambda_{Edd} \). The
Spearman test gives \( \rho = -0.43 \) and \( p = 2.3 \times 10^{-4} \), suggesting a moderate correlation between \( \alpha_{ox} \) and \( \lambda_{Edd} \). All symbols have the same meaning as in Figure 4.

Section 4.1 about the redshift independent relationship between \( k_{bol} \) and \( L_{bol} \).

The Eddington ratio \( \lambda_{Edd} \) is the relative accretion rate of the SMBH. Shenmer et al. (2008) and Lusso et al. (2010) found that a weak correlation exists between \( \alpha_{ox} \) and \( \lambda_{Edd} \) from the analyses of \( \sim 30 \) and \( \sim 150 \) quasars at lower redshifts, respectively. In order to test whether \( \alpha_{ox} \) depends on \( \lambda_{Edd} \) at high redshift, we also correlate \( \alpha_{ox} \) with \( \lambda_{Edd} \) for the 897 SDSS quasars from Timlin et al. (2020) and the \( z > 6.5 \) quasars in Figure 6. Although the relation shows large scatter, a Spearman test gives a correlation coefficient of \( \rho = -0.43 \) and a chance probability of \( p = 2.3 \times 10^{-4} \), suggesting a moderate \( \alpha_{ox} - \lambda_{Edd} \) relation and that the \( \alpha_{ox} \) steepens with increasing \( \lambda_{Edd} \). Our analysis shows a stronger \( \alpha_{ox} - \lambda_{Edd} \) relation compared with that in Shenmer et al. (2008) and Lusso et al. (2010), which could be a natural result of the improved statistics arising from a much larger quasar sample. Nevertheless, the dispersion of this relation is still significant due to the large uncertainty on the individual \( \lambda_{Edd} \) measurements, which has a systematic uncertainty up to \( \sim 0.55 \) dex from the \( M_{BH} \) estimate (Vestergaard & Osmer 2009). On the other hand, we need to keep in mind that \( \lambda_{Edd} \) correlates with \( L_{2500\AA} \), thereby the \( \alpha_{ox} - \lambda_{Edd} \) relation could also be a consequence of the inherent dependence of \( \lambda_{Edd} \) and \( L_{2500\AA} \) as suggested by Shenmer et al. (2008).

In addition to the broadband SED shape, the relative importance of X-ray and UV emission can also affect the radiation driven wind from the accretion disk, where the X-ray photons can strip the gas of electrons and thereby reduce the line driving, while the UV photons accelerate the wind due to
radiation line pressure (the so-called disk-i+wind model; e.g., Proga et al. 2000; Richards et al. 2011). Therefore, the relatively soft spectrum (smaller $\alpha_{ox}$) would drive a strong wind (e.g., Kuczewski et al. 2011). As such, $\alpha_{ox}$ is an important parameter for understanding the radiation driven wind. It is commonly suggested that the blueshift of high-ionization broad emission lines, like C IV, is a marker for radiation driven winds launched from the accretion disk (e.g., Gaskell 1982; Richards et al. 2011). Thus, one would expect the $\alpha_{ox}$ to be correlated with C IV line blueshift. Indeed, a moderate correlation between $\alpha_{ox}$ and C IV line blueshift have been found at low redshifts (e.g., Richards et al. 2011; Timlin et al. 2020) which supports the paradigm discussed above. On the other hand, recent studies found that the C IV line blueshift of the most distant quasars is about a factor of $\sim 2.5$ larger than that of lower redshift quasars (e.g., Mazzucchelli et al. 2017; Meyer et al. 2019; Schindler et al. 2020). Investigations of whether the most distant quasars follow the $\alpha_{ox}$ and C IV line blueshift relation found in lower redshift quasars will give us more insights on whether the radiation driven wind in quasars evolves with redshift. In Figure 7, we show the relation between $\alpha_{ox}$ and C IV line blueshift for both $z > 6.5$ quasars and SDSS lower redshift quasars. The blueshifts were derived from the redshifts of Mg II and C IV lines as listed in Table 3. In this figure, the $z > 6.5$ quasars show higher C IV line blueshifts than most of the SDSS quasars, but they still follow the blue line derived by Timlin et al. (2020) based solely on SDSS $z \sim 2$ redshift quasars. Although J1342+0928, the most distant quasar in our sample, is far from the relation found by Timlin et al. (2020), such outliers in SDSS quasars with smaller blueshift velocities are also seen in this plot. A larger sample of quasars at $z \sim 7$ with both X-ray and NIR observations are needed to shed more light on this question.

4.3. X-Ray versus Infrared Luminosity

The observed relations between the masses of SMBHs and the masses of the bulges in their host galaxy suggest a connection between SMBHs and their host galaxies (see Kormendy & Ho 2013 for a review). The underlying relation between the average host star formation and AGN luminosity found in low redshift high luminosity AGNs (e.g., Alexander et al. 2005; Netzer 2009; Xu et al. 2015) leads to a relationship between bulge and SMBH growth rates. Recent work by Rosario et al. (2012) finds that the relation between star formation and AGN activity in luminous AGNs weakens or disappears at high redshifts ($z > 1$), suggesting an evolutionary relation between SMBH and host galaxy growth rates at high redshifts. In order to investigate whether the quasar X-ray properties (i.e., X-ray luminosity) correlate with quasar host galaxy properties (i.e., $L_{IR}$ or SFR) in the earliest epochs, we plot the $L_{IR}$ and $L_{2-10 \text{ keV}}$ of all objects as described in Section 3 in Figure 8. From Figure 8, there is no correlation ($\rho = -0.19$, $p = 0.10$) between $L_{IR}$ (or SFR) and $L_{2-10 \text{ keV}}$ for both SDSS $z \sim 2$ quasars and high-$z$ quasars, different from that in lower redshift ($z < 1$) AGNs (e.g., Netzer 2009; Xu et al. 2015). The lack of a correlation between $L_{IR}$ and $L_{2-10 \text{ keV}}$ of these luminous quasars is also consistent with the absence of a correlation between $L_{IR}$ and $L_{bol}$ of $z \gtrsim 6$ quasars (Venemans et al. 2018) and the high mass ratio between SMBHs and their host galaxies (e.g., Decarli et al. 2018; Wang et al. 2019a), indicating that SMBHs of the most luminous quasars in the early epochs do not coevolve with their host galaxies, at least not following the same relation found in low redshift galaxies (e.g., Alexander et al. 2005; Netzer 2009; Kormendy & Ho 2013). We emphasize that our quasar sample only represents the UV brightest quasar population at high redshift and the conclusion can only apply to these most luminous objects.

Moreover, Figure 8 shows that the $L_{IR}$ of the most luminous (e.g., $L_{2-10 \text{ keV}} \gtrsim 10^{42} \text{ erg s}^{-1}$) quasars is even fainter than that of X-ray fainter ones (e.g., $L_{2-10 \text{ keV}} < 10^{45} \text{ erg s}^{-1}$) and most SDSS quasars. However, as we mentioned in Section 3, the Herschel detected SDSS quasars only represent the $\sim 15\%$ infrared bright quasars limited by the depth of Herschel observations, thus some of the Herschel undetected SDSS quasars could have similar infrared-to-X-ray luminosity ratios with $z > 6.5$ quasars. Nevertheless, there is no $z > 6.5$ quasar having $L_{IR}$ close to $10^{42} \text{ erg s}^{-1}$ and several X-ray bright high-$z$ quasars with $L_{IR} < 10^{46} \text{ erg s}^{-1}$ suggests that these
powerful AGN with strong disk driven wind, as indicated by the high Eddington ratio (Figure 6) and large CIV blueshift (Figure 7), could suppress star formation activities in their host galaxies. However, our current sample is too small to obtain definitive conclusions and a systematic survey of the X-ray and far-infrared properties of a larger $z > 6.5$ quasar sample would be critical to test this scenario.

5. Average X-Ray Properties of $z \sim 7$ Quasars

Measuring the X-ray spectral properties for individual quasars requires a significant number of detected X-ray counts. In this work, we do not attempt to fit the individual quasar X-ray spectrum due to the limitation of small number of photons detected. Instead, we measure the average hard X-ray photon index of these $z > 6.5$ quasars using two different methods. First, we perform a joint spectral analysis of the six $z > 6.5$ quasars that are well detected in the X-ray (see Table 2). The average redshift of these six quasars is $z = 6.822$ and the total net counts in the 0.5–7 keV band is $\sim 64$. We jointly fit these quasar spectra with a power-law model and associate a value of redshift and Galactic absorption to each source using XSPEC. From the joint fit, we derive a photon index $\Gamma = 2.32^{+0.31}_{-0.30}$. We use the Cash statistic and report the uncertainties at the 68% confidence level. As a further test, we stack the spectra of these six detected $z > 6.5$ quasars. The stacked spectrum is shown in Figure 9. We use XSPEC to fit this stacked spectrum with a power-law by fixing the Galactic absorption component to the mean $N_H$ and the redshift to $z = 6.822$. The derived photon index from the stacked spectrum fitting is $\Gamma = 2.11^{+0.27}_{-0.36}$, consistent with the photon index obtained by the joint spectral fitting.

Vito et al. (2019) jointly analyzed three $z > 6.5$ quasars ($\sim 23$ net counts in total) and found $\Gamma = 2.66^{+0.50}_{-0.54}$. The average $\Gamma$ measured by Vito et al. (2019) is slightly steeper than (although with large uncertainties) the average $\Gamma$ found at lower redshifts, which is $\Gamma \sim 1.9$ (Piconcelli et al. 2005; Vignali et al. 2005; Shemmer et al. 2006; Just et al. 2007; Nanni et al. 2017). In the left panel of Figure 10, we show the average $\Gamma$ measured from joint spectral fitting of quasars at different cosmic epochs.

Our newly measured $\Gamma$ is slightly steeper than that for lower redshift quasars, consistent with the value measured by Vito et al. (2019) but with smaller uncertainties.

With the $\Gamma$ value of a quasar’s hard X-ray spectrum correlates with the $\lambda_{\text{Edd}}$ value as suggested by numerous works (e.g., Porquet et al. 2004; Shemmer et al. 2008; Brightman et al. 2013), it is necessary to check whether the steeper hard X-ray spectral slope at $z > 6.5$ is due to quasars with high Eddington ratios. Since not all quasars studied in these joint spectral analyses (e.g., Porquet et al. 2004; Shemmer et al. 2008; Brightman et al. 2013) have Eddington ratio measurements, we cannot compare the Eddington ratios of these quasars for joint spectral analyses directly. Instead, we compare the average $\Gamma$ and $\lambda_{\text{Edd}}$ of our $z > 6.5$ quasars with the relation found by Brightman et al. (2013) from a well studied AGN sample at $0.5 \lesssim z \lesssim 2.0$ in the Cosmic Evolution Survey (COSMOS) and Extended Chandra Deep Field South (E-CDF-S) field. In the right panel of Figure 10 we show the measurements and relation from Brightman et al. (2013) as well as our measurement at $z > 6.5$. In this figure, we also show the average $\Gamma$ and $\lambda_{\text{Edd}}$ of the $z \gtrsim 6$ quasars from Vito et al. (2019) and SDSS $z \sim 2$ quasars. Note that the average $\Gamma$ of $z \sim 2$ SDSS quasars is directly measured from the X-ray spectral fitting by Timlin et al. (2020) and only includes $\sim 100$ quasars with $> 50$ net counts selected from our $z \sim 2$ comparison quasar sample (see Section 4). This plot indicates that the steeper hard X-ray slope of the $z > 6.5$ quasars from our analysis and the previous study by Vito et al. (2019) are fully consistent with the $\Gamma$ and $\lambda_{\text{Edd}}$ relation found in lower-$z$ quasars, suggesting that the steeper $\Gamma$ of $z > 6.5$ quasars is mainly driven by their higher Eddington ratios rather than by their higher redshifts.

6. Summary

In this paper, we present new Chandra observations of five quasars at $z > 6.5$. By combining them with archival Chandra observations of an additional six $z > 6.5$ quasars, we perform a systematic analysis of the X-ray properties of these reionization-era quasars. Six of these $11 z > 6.5$ quasars are well detected with a luminosity range of $L_{2–10 \text{ keV}} \sim (4.7–35.3) \times 10^{44}$ erg s$^{-1}$. In addition, we analyze the infrared spectroscopic observations of these Chandra observed $z > 6.5$ quasars and derive the bolometric luminosities, BH masses, Eddington ratios, and broad emission line blueshifts for all quasars. The bolometric luminosities of these sources span a range of $L_{\text{bol}} \sim (0.5–3.4) \times 10^{47}$ erg s$^{-1}$, occupying the bright end of the quasar population. Their masses and Eddington ratios are in the range $(0.2–3.0) \times 10^9 M_\odot$, and $\sim 0.3–2.4$, respectively. We also measure the infrared luminosity ($L_{\text{IR}}$) and star formation rate (SFR) of the quasar host galaxies yielding $L_{\text{IR}}$ in the range of $(0.5–4.5) \times 10^{46}$ erg s$^{-1}$ and SFR in the range of $\sim 200–2000 M_\odot$ yr$^{-1}$, respectively. Moreover, we perform a joint spectral analyses of all X-ray detected quasars and measure the average X-ray spectral properties of these $z > 6.5$ quasars. Our findings from this unique sample of $z > 6.5$ quasar with both X-ray and near-infrared spectroscopic observations, and based on a comparison quasar sample at $z \sim 2$, are as follows:

1. The X-ray bolometric luminosity correction ($k_{\text{bol}} = L_{\text{bol}} / L_{2–10 \text{ keV}}$) of $z > 6.5$ quasars increases with bolometric luminosity and the optical/UV to X-ray flux ratio, $\alpha_{\text{ox}}$, strongly correlates with quasar luminosity at rest-frame.
2500 Å, $L_{2500}$, following the same trend found in lower redshift quasars.

2. A moderate correlation between $\alpha_{\text{ox}}$ and Eddington ratio, $\lambda_{\text{Edd}}$, exists. This correlation is weaker than the $\alpha_{\text{ox}}-L_{2500}$ relation, which could either be a consequence of the inherent dependence of $\lambda_{\text{Edd}}$ and $L_{2500}$ or result from the large uncertainty introduced by the $\lambda_{\text{Edd}}$ measurement.

3. The $L_{2500}$ and SFR do not correlate with the $L_{2.10}$ keV in these luminous distant quasars, suggesting that the ratio of the SMBH growth rate and their host galaxy growth rate in these early luminous quasars are different from that of local galaxies.

4. There is a moderate correlation between $\alpha_{\text{ox}}$ and CIV line blueshift. In the disk+wind model picture (e.g., Gaskell 1982; Richards et al. 2011), the CIV line blueshift increases as the relative importance of corona X-ray emission and accretion disk emission decreases, consistent with the observed correlation.

5. The average photon index, $\Gamma$, of hard X-ray spectra of $z > 6.5$ quasars is found to be $\Gamma = 2.32^{+0.31}_{-0.30}$, steeper than that of lower redshift quasars. By comparing our measurement with the $\Gamma-\lambda_{\text{Edd}}$ relation found in lower redshift quasars (e.g., Brightman et al. 2013), we conclude that the steeper $\Gamma$ of $z > 6.5$ quasars is mainly driven by their higher Eddington ratios rather than by their higher redshifts.

In the near future, a larger sample of $z > 6.5$ quasars with both X-ray, NIR, and submillimeter observations, as well as a well matched (in terms of both quasar luminosity and observational depth) quasar sample at lower redshifts is critical for investigating whether the earliest SMBHs are fed by different accretion physics (especially the X-ray luminosity and $\Gamma$) and arise in distinct galactic environments (i.e., star formation rate) relative to their lower redshift counterparts.

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OBJECTIVE: To identify and analyze the key findings and methodologies presented in the document.

Methods:
- Review the scientific literature on the topic
- Analyze the data presented in the document
- Synthesize the findings and conclusions of the study

Results:
- Key findings
- Methodological approaches
- Implications for future research

Conclusions:
- The study highlights the importance of interdisciplinary collaboration.
- Further research is needed to address the limitations identified in the study.
- The findings have implications for policy and practice in the field.

References:
- List of sources cited in the document
- Additional resources for further reading

Appendices:
- Additional data tables
- Figures and graphs
- Supplementary materials

Figures:
- Graphs and charts representing the data
- Diagrams illustrating the methodology

Tables:
- Summary of key results
- Comparison of data across different categories
- Cross-tabulations of relevant variables

Supplementary materials:
- Additional data sets
- Code and scripts used in the analysis
- Detailed methodology sections

Appendices:
- Supplementary tables and figures
- Further elaboration on the methodology
- Additional case studies

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