Steep Hard-X-Ray Spectra Indicate Extremely High Accretion Rates in Weak Emission-line Quasars*

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Abstract

We present XMM-Newton imaging spectroscopy of 10 weak emission-line quasars (WLQs) at 0.928 ≤ z ≤ 3.767, six of which are radio-quiet, and four that are radio-intermediate. The new X-ray data enabled us to measure the power-law photon index, at rest-frame energies >2 keV, in each source with relatively high accuracy. These measurements allowed us to confirm previous reports that WLQs have steeper X-ray spectra, suggesting higher accretion rates with respect to “typical” quasars. A comparison between the photon indices of our radio-quiet WLQs and those of a control sample of 85 sources shows that the first are significantly higher, at the ≥3σ level. Collectively, the four radio-intermediate WLQs have lower photon indices with respect to the six radio-quiet WLQs, as may be expected if the spectra of the first group are contaminated by X-ray emission from a jet. Therefore, in the absence of significant jet emission along our line of sight, these results are in agreement with the idea that WLQs constitute the extreme high end of the accretion-rate distribution in quasars. We detect soft excess emission in our lowest-redshift radio-quiet WLQ, in agreement with previous findings suggesting that the prominence of this feature is associated with a high accretion rate. We have not detected signatures of Compton reflection, Fe Kα lines, or strong variability between two X-ray epochs in any of our WLQs, which can be attributed to their relatively high luminosity.

Key words: galaxies: active – galaxies: nuclei – quasars: emission lines – quasars: general – X-rays: galaxies

1. Introduction

It is common to classify weak emission-line quasars (WLQs) as luminous active galactic nuclei (AGN) with rest-frame equivalent widths (EWs) of either <15.4 Å or <10.0 Å for the Lyα+N V λ1240 emission complex or C IV λ1549 emission line, respectively (Diamond-Stanic et al. 2009). These thresholds mark the 3σ limit at the low-EW tail of the respective EW distributions in Sloan Digital Sky Survey (SDSS; York et al. 2000) quasars. Based on this classification, ≈107 WLQs are known, to date, discovered mainly by the SDSS (e.g., Fan et al. 1999; Anderson et al. 2001; Collinge et al. 2005; Plotkin et al. 2010; Meusinger & Balafkan 2014), but also by other surveys (e.g., McDowell et al. 1995; Londish et al. 2004). Interestingly, the fraction of WLQs among quasars appears to increase sharply from ~0.1% at 2 ≤ z ≤ 5 to ≥15% at z ≥ 6 (e.g., Fan et al. 2006; Diamond-Stanic et al. 2009; Bañados et al. 2016). Identifying the cause(s) for their line weakness is therefore important for understanding the physical conditions in the early universe.

Multiwavelength and multi-epoch observations of several sub-samples of WLQs have shown that they are unlikely to be high-redshift galaxies with apparent quasar-like luminosities due to gravitational-lensing amplification, dust-obscured quasars, or broad absorption line (BAL) quasars (e.g., Shemmer et al. 2006; Diamond-Stanic et al. 2009). Additionally, the radio and X-ray properties of WLQs indicate that they are unlikely to be identified as high-redshift BL Lacertae objects (Shemmer et al. 2009; Plotkin et al. 2010; Lane et al. 2011). Therefore, the emission lines in WLQs are considered to be intrinsically weak.

Several proposals have been put forward that attempted to explain the intrinsic emission-line weakness in WLQs. One of these suggested that the broad emission-line regions (BELRs) in WLQs have either abnormal physical properties (e.g., lack of line-emitting gas, or a low covering factor), or are in the early stages of formation (e.g., Hryniewicz et al. 2010; Liu & Zhang 2011). Although such ideas may appear promising in their attempt to explain the increasing fraction of WLQs as a function of redshift, they face several difficulties, mainly on physical grounds. A different model, suggesting a relatively cold accretion disk, as a result of an unusually high supermassive black hole mass and low accretion rate (Laor & Davis 2011),
faces its own challenges. In particular, a predicted sharp cutoff in the spectral energy distribution (SED) at $\lambda_{\text{rest}} \lesssim 1000$ Å has not yet been detected following observations of several WLQ sub-samples.

The most promising path to identifying the underlying reason for intrinsic BELR line weakness in quasars originates from what is known as the Baldwin effect, which is an anti-correlation between BELR line EW and quasar luminosity (Baldwin 1977). In its modified form, this effect involves an anti-correlation between BELR line EW and the Eddington fraction (i.e., $L/L_{\text{Edd}}$, where $L$ and $L_{\text{Edd}}$ are the bolometric and Eddington luminosity, respectively; e.g., Baskin & Laor 2004; Dong et al. 2009; Shemmer & Lieber 2015). The idea that a high Eddington fraction, corresponding to a high normalized accretion rate, is responsible for intrinsic line weakness, has been proposed in various studies. For example, Leighly et al. (2007a, 2007b) have suggested that an extremely high accretion rate would result in a modified, UV-peaked SED lacking high-energy ionizing photons (see also Vaselinev & Fabian 2007). However, such a model necessarily predicts unusual X-ray weakness, with respect to the optical emission, which is not observed in all WLQs (e.g., Wu et al. 2011, 2012; Luo et al. 2015). Quantification of this X-ray weakness is based on the optical-X-ray spectral slope, defined as $\alpha_{\text{ox}} = \log(f_{2\text{keV}}/f_{2500\AA})/\log(f_{2\text{keV}}/f_{2500\AA})$, where $f_{2\text{keV}}$ and $f_{2500\AA}$ are the flux densities at 2 keV and 2500 Å, respectively. This parameter is strongly correlated with the luminosity density at 2500 Å, $L_{\text{ox}}(2500\AA)$ (e.g., Just et al. 2007; Lusso & Risaliti 2016). According to Luo et al. (2015), a quasar is considered to be X-ray weak if it has an observed $\alpha_{\text{ox}}$ value that is lower by at least 0.2 from the expected value based on the $\alpha_{\text{ox}}$–$L_{\text{ox}}$(2500 Å) correlation, i.e., $\Delta \alpha_{\text{ox}} < -0.2$; otherwise, it is considered X-ray “normal.”

In order to accommodate the wide range of optical-to-X-ray flux ratios in WLQs, as well as their other properties, Wu et al. (2011) and Luo et al. (2015) have proposed an alternative model that also predicts extremely high accretion rates as a primary ingredient to explain quasar emission-line weakness. Unlike the modified SED scenario, this model predicts that the highly ionizing photons are absorbed by a shielding-gas component, growing vertically from the inner accretion disk, perhaps as the accretion rate rises above a certain threshold. This shielding-gas component may be physically identified with the thick inner accretion disk. The range in relative X-ray weakness is thus explained by a range of viewing angles to the central X-ray source. When viewed at large inclination angles (i.e., closer to a “pole on” view), a WLQ will appear to have “normal” X-ray emission with respect to its optical emission; when viewed at smaller inclination angles, a portion of the X-ray emission is absorbed by the shielding gas, resulting in an X-ray-weak WLQ. This model is supported by observations of X-ray-weak WLQs that show considerably harder X-ray spectra with respect to typical quasars, indicating heavy intrinsic absorption in such sources (Wu et al. 2011, 2012; Luo et al. 2015).

However, when compared to typical quasars over wide ranges of redshift and luminosity, WLQs do not appear to follow the strong EW–$L/L_{\text{Edd}}$ anti-correlation, where $L/L_{\text{Edd}}$ estimates are based on the H$\beta$ line (Shemmer & Lieber 2015). The EWs of their C IV emission lines predict $L/L_{\text{Edd}}$ values that are a factor of $\approx 5$ larger than estimated. This discrepancy may imply that either (i) there are other factors that regulate emission-line strength in quasars, or (ii) the H$\beta$ line cannot be used to obtain reliable $L/L_{\text{Edd}}$ estimates for all quasars. The X-ray power-law photon index ($\Gamma$), particularly when measured above $\approx 2$ keV in the rest-frame, has been identified as a more robust proxy for estimating $L/L_{\text{Edd}}$ in quasars (e.g., Shemmer et al. 2006, 2008; Constantini et al. 2009; Brightman et al. 2013; Fanali et al. 2013). In particular, Risaliti et al. (2009) found a strong correlation ($r = 0.56$ and $p < 10^{-8}$) between $\Gamma$ and H$\beta$-based $L/L_{\text{Edd}}$ in a sample of 82 SDSS quasars with XMM-Newton observations. Accurate measurements of $\Gamma$ in a sizable sample of WLQs can therefore provide an independent indicator of their accretion rates.

The first steps in this direction were taken by Shemmer et al. (2009) and Luo et al. (2015) who jointly fitted X-ray data of 7 and 18 WLQs, respectively, obtained from shallow Chandra X-ray Observatory (hereafter, Chandra; Weisskopf et al. 2000) observations (see also Wu et al. 2012). The first of these studies measured a $\langle \Gamma \rangle = 1.81^{+0.45}_{-0.43}$ in the observed-frame 0.5–8 keV range, concluding that this value is consistent with the values measured in typical type 1 quasars. However, their small sample included a mixture of X-ray weak and X-ray normal WLQs with extremely limited photon statistics (hence the large uncertainty on $\langle \Gamma \rangle$). The second study measured $\langle \Gamma \rangle = 2.18 \pm 0.09$ in the rest-frame $>2$ keV band for a well-selected sample of X-ray normal WLQs with considerably better photon statistics, thereby reducing the uncertainty on $\langle \Gamma \rangle$ by a factor of $\approx 5$. This recent result shows that X-ray normal WLQs have, on average, a higher than normal photon index that indicates a high $L/L_{\text{Edd}}$ value. It also demonstrates the power of sample averaging in the presence of non-negligible intrinsic scatter that is inherent in the $\Gamma$–$L/L_{\text{Edd}}$ correlation.

In this work we aim to obtain accurate measurements of $\Gamma$ values in a sample of individual X-ray normal WLQs in order to determine the extent that these values deviate from the distribution of $\Gamma$ values in typical type 1 quasars. For this purpose, we obtained XMM-Newton (Jansen et al. 2001) observations of nine high-redshift WLQs discovered by the SDSS that were detected by Chandra. Prior to this investigation, only two such sources were observed by XMM-Newton; one was targeted, and the other was observed serendipitously. We include these two sources in our analysis. We describe our sample selection, observations, and data reduction in Section 2; in Section 3 we present the results from our X-ray imaging spectroscopy of WLQs and compare them with similar data for a carefully selected sample of typical quasars. A summary is given in Section 4. Throughout this work we compute luminosity distances using the standard cosmological model ($H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.7$, and $\Omega_{\Lambda} = 0.3$; Spergel et al. 2007). Complete source names appear in the tables, and abbreviated names appear in figures and throughout the text. Unless noted otherwise, hard X-ray refers to the $>2$ keV energy range in the rest-frame, and $N_{\text{HI}}(N_{\text{HI}})\text{d}$ refers to the intrinsic (Galactic) neutral absorption column density.

2. Target Selection, Observations, and Data Reduction

We selected nine SDSS, X-ray normal WLQs at $0.928 \lesssim z \lesssim 3.767$ in order of decreasing X-ray brightness based on previous Chandra detections (Shemmer et al. 2009; Wu et al. 2012; Luo et al. 2015). These sources were predicted to provide sufficient X-ray counts to allow an investigation of their X-ray spectra with economical XMM-Newton observations. As a consequence of our selection algorithm, the two X-ray
The brightest targets are also radio-intermediate (10 < $R < 100$; Kellermann et al. 1989), assuming a jet is contributing to the radio and X-ray emissions; the rest are radio-quiet. By selection, all of our sources are X-ray-normal (Luo et al. 2015) and they have $-0.14 < \Delta_{\alpha} < +0.35$.

The XMM-Newton observation log appears in Table 1. Column (1) gives the SDSS quasar name; columns (2) and (3) give the redshift from the SDSS Data Release 7 (Shen et al. 2011), and the systemic redshift, respectively; column (4) gives the Galactic absorption column density in units of $10^{20}$ cm$^{-2}$, taken from Dickey & Lockman (1990) and obtained with the HEASARC N$_H$ tool; columns (5) and (6) give the XMM-Newton observation ID number and start date, respectively; columns (7)–(12) give the net exposure times and source counts of the MOS1, MOS2, and pn detectors, respectively (these exposure times represent the live time following the removal of flaring periods, and the source counts are in the 0.2–12.0 keV band); column (13) gives the radio-loudness parameter (Kellermann et al. 1989); column (14) gives the Galactic absorption-corrected flux in the observed-frame 0.5–2 keV in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$ taken from previous Chandra data; column (15) gives the reference to the WLQ classification of a source.

Table 1 includes two additional, radio-intermediate WLQs. The results from an XMM-Newton observation of the first of these, SDSS J1141+0219 (at $z = 3.55$), have been presented in Shemmer et al. (2010); we reanalyze this observation for consistency with the rest of our sample. The second source, SDSS J1012+5313 (at $z = 2.99$), has been observed serendipitously by XMM-Newton (see below for more details).

The data were processed using standard XMM-Newton Science Analysis System (SAS) v16.0.0 tasks. All but three objects (discussed below) showed no background flaring activity, and therefore were not filtered in time.

For SDSS J0908+2852, the majority of the observation was subject to flaring, and therefore this object has been removed from all our analyses below.

For SDSS J1141+0219 and SDSS J1147+0733, the event files were filtered in time to remove periods of flaring activity in which the count rates for each MOS (pn) detector exceeded 1.0 (5.0) counts s$^{-1}$ for SDSS J1141+0219, and 0.5 (1.0) counts s$^{-1}$ for SDSS J1147+0733. The higher thresholds used for SDSS J1141+0219 are a consequence of the longer period of flaring activity in this observation. Using a lower threshold, e.g., 0.35 (1.0) counts s$^{-1}$ as used in Shemmer et al. (2010), would have resulted in a larger fraction of the observation being discarded.

For all objects except SDSS J1012+5313 (discussed below), source counts were extracted from each detector using a circular aperture with $r = 30''$ centered on the source. Background counts were extracted from a collection of 3′-4′ nearby source-free regions that were at least as large as the corresponding source region.

SDSS J1012+5313 is serendipitously detected with an angular offset of 2′′845 from the aimpoint. Therefore, we extracted the source counts from a larger circular aperture with $r = 48''$ for the MOS detectors, and $r = 55''$ for the pn detector. These larger regions are expected to capture ~90% of the encircled energy. Background counts were extracted as above. This object also has a previous XMM-Newton observation, ID 0111100201, which is of low quality and is not useful for our purposes (see Shemmer et al. 2009).

We note that the observation of SDSS J1643+4414 experienced intervals during which the telemetry allocation for the detector was saturated, either due to a bright source level, or to a high background; however, we do not find any indication that this may have significantly affected the source and associated background event files.

For all objects, the spectrum from each detector was grouped with a minimum of 20 counts per bin, using the High Energy Astrophysics Science Archive Research Center (HEASARC) FTOOLS task GRPPHA. The net exposure times (i.e., following the removal of periods of flaring activity) and ungrouped source counts in the 0.2–12.0 keV observed-frame band are given in Table 1.

We used XSPEC v12.9.1 (Arnaud 1996) to jointly fit the three EPIC detector data sets for each object at rest-frame energies greater than 2 keV with a power-law model and a Galactic absorption component (i.e., PHABS*POWERLAW model in XSPEC), which was kept fixed during the fit, as well as a similar model with an added intrinsic neutral absorption component (i.e., PHABS*zPHABS*POWERLAW model in XSPEC); we used $\chi^2$-statistics for all these fits. For all but one object, the best fits rely on the PHABS*POWERLAW absorption model in XSPEC. For SDSS J0928+1848, an F-test shows that a model including the ZPHABS component provides a better fit (although, as can be seen from Table 2, the constraints on the neutral absorption column density in this source are not particularly strong).

The best-fit X-ray spectral parameters as well as the optical properties of our sample are given in Table 2. Column (1) gives the SDSS quasar name; columns (2)–(4) give the best-fit values, power-law normalizations, and $\chi^2$ values, respectively, in the rest-frame >2 keV energy range; column (5) shows the upper limits on intrinsic neutral absorption column density ($N_{\text{H}}$); column (6) gives the monochromatic luminosity at a rest-frame wavelength of 2500 Å [$L_{\alpha}(2500 \text{ Å})$]; columns (7) and (8) give the $\alpha_{\text{ox}}$ and the $\Delta\alpha_{\text{ox}}$ parameter, which is the difference between the measured $\alpha_{\text{ox}}$ and the predicted $\alpha_{\text{ox}}$, based on the $\alpha_{\text{ox}}$–$L_{\alpha}(2500 \text{ Å})$ relation in quasars (given as Equation (3) of Just et al. 2007); both parameters are taken from the archival Chandra observations of each source. Column (9) shows the distance values as measured from our XMM-Newton data and the optical data from column (6); column (10) gives the time separation between the Chandra and XMM-Newton epochs in the rest-frame; column (11) gives the photon index obtained from fitting the X-ray spectrum in the observed-frame 0.5–8 keV band (see Section 3.1 for more details). Figures 1 and 2 present the XMM-Newton data, their joint, best-fit spectra, and residuals. Correspondingly, Figures 3 and 4 show the 68%, 90%, and 99% confidence regions for the photon index versus intrinsic neutral absorption column density resulting from those fits when a neutral intrinsic absorption component is included.

In order to obtain better constraints on the $\Gamma$ values of WLQs, as a group, we performed a series of joint spectral fitting of all of our sources in the >2 keV rest-frame energy range. Table 3 presents the results of joint-fitting the spectra of

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14 The radio loudness parameter, $R$, is defined as $f_{\text{5GHz}}/f_{\text{5313}}$, where $f_{\text{5GHz}}$ and $f_{\text{5313}}$ are the flux densities at 5 GHz and 4400 Å, respectively. Radio-quiet (loud) objects are defined as having $R < 10$ ($R > 100$).
15 https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl
16 http://xmm.esac.esa.int/sas
17 This radius corresponds to ~85% of the encircled energy for each detector.

See Section 3.2.1.1 of the XMM-Newton Users Handbook (https://xmm-tools.cosmos.esa.int/external/xmm_user_support/documentation/uhb/).
| WLQ                      | \(z^a\) | \(z_{\mathrm{sys}}^b\) | \(N_{\mathrm{H,Gal}}^c\) | Observation ID | Start Date | Exp Time (ks) | Counts | Exp Time (ks) | Counts | Exp Time (ks) | Counts | References |
|--------------------------|---------|-----------------|-----------------|----------------|------------|---------------|--------|---------------|--------|---------------|--------|------------|
| SDSS J090843.25+285229.8 | 0.930   | ...             | 2.46            | 0760740101     | 2015 Oct 15| 17.1          | ...    | 16.9          | ...    | 12.7         | ...    | <2.0\(^i\) |
| SDSS J092832.87+184824.3 | 3.767   | ...             | 3.83            | 0692510201     | 2012 Oct 24| 29.3          | 246    | 29.3          | 309    | 24.9         | 996    | 14.7\(^i\) |
| SDSS J101204.04+531331.8 | 2.990   | ...             | 0.78            | 0651420201     | 2010 Oct 17| 16.4          | 120    | 16.4          | 84     | 13.1         | 424    | 24.1\(^i\) |
| SDSS J114153.34+021924.3 | 3.480   | 3.550\(^c\)    | 2.30            | 0551750301     | 2008 Jun 27| 20.3          | 162    | 20.3          | 223    | 16.6         | 798    | 14.7\(^i\) |
| SDSS J123132.37+013814.0 | 3.229   | ...             | 1.81            | 0692510101     | 2012 Jun 22| 19.1          | 270    | 19.1          | 288    | 15.7         | 957    | 39.5\(^i\) |
| SDSS J141141.96+140233.9 | 1.745   | 1.754           | 1.43            | 0760740201     | 2015 Jun 30| 18.5          | 207    | 18.5          | 253    | 15.2         | 700    | <3.6\(^i\) |
| SDSS J141730.92+073320.7 | 1.704   | 1.716           | 2.12            | 0782360101     | 2017 Jan 4 | 21.3          | 82     | 21.3          | 81     | 17.5         | 265    | <3.0\(^i\) |
| SDSS J142943.64+35932.2 | 0.928   | ...             | 0.95            | 0760740401     | 2015 Jun 10| 25.4          | 166    | 25.4          | 122    | 21.4         | 481    | <0.9\(^i\) |
| SDSS J144741.76–020339.1 | 1.427   | 1.430           | 4.53            | 0782360201     | 2016 Jul 19| 36.0          | 223    | 36.0          | 229    | 30.6         | 731    | <2.3\(^i\) |
| SDSS J161245.70+511816.9 | 1.595   | ...             | 1.67            | 0743305051     | 2014 Aug 8 | 35.3          | 308    | 35.0          | 385    | 29.8         | 1103   | <1.5\(^i\) |
| SDSS J164302.03+441422.1 | 1.650   | ...             | 1.52            | 0760740301     | 2015 Jun 24| 17.7          | 357    | 17.4          | 442    | 15.7         | 1183   | <3.1\(^i\) |

Notes.

\(^a\) Redshift from SDSS Data Release 7 (Shen et al. 2011).
\(^b\) Systemic redshift; unless otherwise noted, obtained from Plotkin et al. (2015). We use this redshift when available, otherwise we use the redshift from column (2).
\(^c\) Neutral Galactic absorption column density in units of 10\(^{20}\) cm\(^{-2}\) obtained from Dickey & Lockman (1990).
\(^d\) Radio-loudness parameter (Kellermann et al. 1989).
\(^e\) Galactic absorption-corrected flux in the observed-frame 0.5–2 keV in units of 10\(^{-15}\) erg cm\(^{-2}\) s\(^{-1}\) taken from previous Chandra data.
\(^f\) Observation completely ruined by background flaring.
\(^g\) Serendipitous observation.
\(^h\) Obtained from Shemmer et al. (2010).
\(^i\) Obtained from Luo et al. (2015).
\(^j\) Obtained from Shemmer et al. (2009).
\(^k\) Obtained from Wu et al. (2012).
\(^l\) Observation affected by auto-stack problem; pn experienced Full Scientific Buffer during the whole exposure; see the text for more details.

References. (1) Plotkin et al. (2010), (2) Shemmer et al. (2009), (3) Schneider et al. (2007), (4) Collinge et al. (2005).
Table 2
Best-fit X-Ray Spectral Parameters and Optical Properties

| WLQ (1)          | Γ (2)   | $f_X$ (1 keV)$^a$ | $\chi^2$/d.o.f. (3) | $N_h^b$ | log $v_{in}$ (2500 Å) (erg s$^{-1}$) | $\alpha_{ox}$ (7) | $\Delta \alpha_{ox}$ (8) | $\alpha_{ox}$ (9) | $\Delta t^d$ (days) | $\Gamma_{0.5-4\, keV}^e$ |
|------------------|---------|-------------------|----------------------|---------|----------------------------------|------------------|------------------------|------------------|------------------|------------------|
|                  |         |                   |                      |         | Chandra                           | XMM-Newton        |                       |                  |                  |                  |
| Radio-intermediate |         |                   |                      |         |                                  |                  |                       |                  |                  |                  |
| SDSS J092832.87+184824.3 | 1.82 ± 0.13 | 14.5$^{+1.9}_{-1.7}$ | 67/70 | $1.7^{+1.4}_{-1.3}$ | 47.2$^a$ | $-1.59^g$ | +0.20 | -1.59 | 445 | 1.65$^{+0.62}_{-0.28}$ |
| SDSS J101204.04+531331.8 | 1.67$^{+0.64}_{-0.48}$ | 3.8 ± 1.1 | 18/27 | $\leq 3.7$ | 46.3$^g$ | $-1.49^g$ | +0.18 | -1.56 | 869 | 2.14$^{+1.02}_{-0.08}$ |
| SDSS J114153.34+021924.3 | 1.93$^{+0.26}_{-0.23}$ | 6.8 ± 1.0 | 59/54 | $\leq 3.9$ | 46.7$^g$ | $-1.54^g$ | +0.18 | -1.55 | 111 | 2.18$^{+0.40}_{-0.12}$ |
| SDSS J123132.37+013814.0 | 1.91$^{+0.11}_{-0.10}$ | 17.2 ± 1.3 | 67/69 | $\leq 1.4$ | 46.7$^g$ | $-1.37^g$ | +0.35 | -1.43 | 429 | 1.71$^{+0.24}_{-0.33}$ |
|                  |         |                   |                      |         |                                  |                  |                       |                  |                  |                  |
| Radio-quiet |         |                   |                      |         |                                  |                  |                       |                  |                  |                  |
| SDSS J141141.96+140233.9 | 2.36$^{+0.14}_{-0.13}$ | 24.0 ± 2.0 | 65/51 | $\leq 0.8$ | 46.0$^h$ | $-1.42^h$ | +0.20 | -1.35 | 336 | 2.75$^{+0.93}_{-0.49}$ |
| SDSS J141730.92+073320.7 | 2.25$^{+0.51}_{-0.42}$ | 5.2 ± 1.1 | 22/17 | $\leq 0.9$ | 46.1$^h$ | $-1.56^h$ | +0.08 | -1.67 | 549 | 2.75$^{+0.69}_{-0.38}$ |
| SDSS J142943.64+385932.2 | 2.63$^{+0.27}_{-0.25}$ | 19.7$^{+1.1}_{-1.8}$ | 28/33 | $\leq 0.8$ | 45.9$^h$ | $-1.73^h$ | +0.11 | -1.62 | 474 | 4.51$^{+0.39}_{-0.46}$ |
| SDSS J144741.76−020339.1 | 2.21$^{+0.16}_{-0.15}$ | 11.0$^{+1.3}_{-1.2}$ | 52/53 | $\leq 0.8$ | 46.0$^h$ | $-1.76^h$ | -0.14 | -1.55 | 528 | 2.41$^{+0.29}_{-0.13}$ |
| SDSS J161245.70+511816.9 | 2.68$^{+0.14}_{-0.13}$ | 20.5$^{+1.2}_{-1.4}$ | 76/79 | $\leq 0.6$ | 46.4$^i$ | $-1.67^i$ | +0.01 | -1.57 | 495 | 2.89$^{+0.22}_{-0.18}$ |
| SDSS J164302.03+441422.1 | 1.88 ± 0.10 | 32.2 ± 2.2 | 86/90 | $\leq 0.4$ | 46.0$^h$ | $-1.43^h$ | +0.19 | -1.31 | 285 | 2.04$^{+0.20}_{-0.15}$ |

Notes. Unless otherwise noted, the best-fit photon index, normalization, and $\chi^2$ were obtained from a Galactic absorbed power-law model. The errors represent 90% confidence limits, taking one parameter of interest ($\Delta \chi^2 = 2.71$). The photon index in column (2) was measured in the rest-frame $\gtrsim 2$ keV energy range.

$^a$ Power-law normalization given as the flux density at an observed-frame energy of 1 keV with units of $10^{-32}\text{ erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}$; this refers to the pn data, and except for one source, was taken from joint-fitting of all three EPIC detectors with the Galactic absorbed power-law model. The data for SDSS J092832.87+184824.3 was taken with the Galactic absorbed power-law model with an added neutral intrinsic absorption component.

$^b$ Intrinsic neutral absorption column density in units of $10^{22}\text{ cm}^{-2}$. Upper limits were computed with the intrinsically absorbed power-law model with Galactic absorption, and represent 90% confidence limits for each value.

$^c$ The difference between the measured $\alpha_{ox}$ from column (7) and the predicted $\alpha_{ox}$ based on the $\alpha_{ox}$-$L_\odot$ (2500 Å) relation (given as Equation (3) of Just et al. 2007).

$^d$ Time separation between the Chandra and XMM-Newton epochs in the rest-frame.

$^e$ Photon index obtained from fitting the X-ray spectrum in the observed-frame 0.5–8 keV band using the PEXRAV model in XSPEC (see Section 3.1 for more details).

$^f$ X-ray spectral parameters were obtained from a Galactic absorbed power-law model that included an intrinsic absorption component.

$^g$ Obtained from Shemmer et al. (2009).

$^h$ Obtained from Luo et al. (2015).

$^i$ Obtained from Wu et al. (2012).
all four radio-intermediate sources and all six radio-quiet sources, separately. Columns (1) and (2) give the run sequence and number of sources per run, respectively; column (3) gives the mean and median redshifts; column (4) gives the mean intrinsic neutral absorption column density ($N_{\text{H}}$); columns (5) and (6) give the mean, best-fit $\Gamma$ values and $\chi^2$ values, respectively, in the rest-frame $>2$ keV range. The joint-fitting was performed three times using the same models as noted above for the individual sources. The first run was completed with objects from Table 2 that are radio-intermediate; the second run is similar to the first, but excluding SDSS J1012+5313, which has a relatively lower-quality data set. The third run included all the objects from Table 2 that are radio-quiet. Figure 5 shows the contour plots of the $\Gamma$–$N_{\text{H}}$ parameter space from each joint-fitting run. The results of our joint-fitting show that the radio-quiet and radio-intermediate objects (excluding SDSS J1012+5313) have significantly different mean $\Gamma$ values, with the first group having significantly steeper X-ray spectra, and there is no detection of significant intrinsic absorption.

3. Results and Discussion

3.1. How Extreme are the Hard-X-Ray Spectral Slopes of WLQs?

Type 1 quasars are known to exhibit a hard X-ray spectral slope of $\Gamma \sim 1.8–2.0$ across the universe (e.g., Reeves & Turner 2000; Page et al. 2005; Piconcelli et al. 2005; Shemmer et al. 2005; Vignali et al. 2005; Just et al. 2007; Young et al. 2009)
that appears to be regulated by $L/L_{\text{Edd}}$ (Shemmer et al. 2008). Based upon the well-known $\Gamma - L/L_{\text{Edd}}$ correlation, the small fraction of quasars with measured $\Gamma$ values of $\gtrsim 2.2$ is interpreted as sources that accrete close to or even above the Eddington limit (e.g., Risaliti et al. 2009). A natural explanation for the mean $\Gamma$ value of $2.18 \pm 0.09$, measured for 18 X-ray normal WLQs by Luo et al. (2015), is that these sources lie at the extreme high end of the $L/L_{\text{Edd}}$ distribution in quasars. Quantifying, or constraining, their deviations from that distribution can be done by obtaining a deeper X-ray observation for each individual source.

Our data provide almost an order of magnitude increase in the number of X-ray counts for radio-quiet and X-ray normal WLQs, and they confirm the basic Luo et al. (2015) finding. Table 2 shows that most of our radio-quiet sources have extremely high $\Gamma$ values, and the mean $\Gamma$ value of these sources, $\langle \Gamma \rangle = 2.30 \pm 0.06$, based on jointly fitting their spectra (Table 3), is larger than, yet consistent within the errors with, the Luo et al. (2015) value. In order to quantify the extremity of the $\Gamma$ values of these WLQs, we searched the literature and X-ray archives to identify the most suitable comparison sample of quasars.

The sample of Liu et al. (2016; hereafter L16) includes 1786 type I quasars observed with XMM-Newton as part of the XMM-XXL-North survey; this is one of the largest samples of X-ray detected quasars to date. Of these, 1731 sources are part of the SDSS Data Release 12 quasar catalog (Pâris et al. 2017), which are covered in the Faint Images of the Radio Sky at Twenty cm (FIRST; Becker et al. 1995) footprint. We further limited this sample by requiring each source to meet all of the following criteria:

1. pn counts $> 100$
2. BAL flag equals zero for sources at $z > 1.57$, according to the Pâris et al. (2017) catalog
3. radio-quiet sources having $R < 10$. 

Figure 2. Data, best-fit spectra, and residuals of XMM-Newton observations of our radio-quiet WLQs. The symbols are similar to those of Figure 1.
The first of these criteria ensures that sources have X-ray data with comparable quality to our WLQ observations (a higher pn counts threshold would have limited the sample considerably; see Figure 6). The second criterion is set to minimize the effects of X-ray absorption (e.g., Gallagher et al. 2006), and the third criterion is required for minimizing the potential contribution of a jet to the X-ray emission (e.g., Miller et al. 2011).
Figure 4. Same as Figure 3, but for our radio-quiet WLQs.

Table 3

| Run Description                        | Number of Sources | Mean (Median) Redshift | \(N_H\) \((10^{22} \text{ cm}^{-2})\) | \(\Gamma\) | \(\chi^2/(\text{d.o.f.})\) |
|----------------------------------------|-------------------|------------------------|-------------------------------------|---------|-----------------|
| Radio Intermediate\(^a\)              | 4                 | 3.38 (3.39)            | 0.80\(^{+0.94}_{-0.78}\)           | 1.86 ± 0.10 | 236/231        |
| Radio Intermediate (excluding SDSS J1012+5313) | 3                 | 3.52 (3.55)            | \(\leq 1.33\)                      | 1.79 ± 0.06 | 214/201        |
| Radio Quiet                            | 6                 | 1.51 (1.62)            | \(\leq 0.07\)                      | 2.30 ± 0.06 | 428/349        |

Note. Best-fit parameters of joint-fitting the spectra in the >2 keV rest-frame energy range with a power-law model and Galactic absorption.

\(^a\) X-ray spectral parameters were obtained from a Galactic absorbed power-law model that included an intrinsic neutral absorption component.
There are 167 L16 sources that meet the first criterion, 48 of which are at $z > 1.57$. One of these 48 sources is flagged as a BAL quasar by Pâris et al. (2017) and is therefore removed from our sample. Based on the BAL fraction at $z > 1.57$, we expect that $\sim 2$–3 BAL quasars may be present among the remaining 119 sources at $z < 1.57$. Cross-matching with the FIRST catalog, using a 2″ search radius around the SDSS coordinates of each source (see, e.g., Pâris et al. 2017), yielded 15 radio counterparts to the remaining 166 L16 sources. Two additional sources, out of 166, have FIRST detections with angular offsets of 2″2 and 2″7; we consider these to be physically related to the respective L16 sources, thus raising the total number of radio counterparts to 17.

The $R$ values for the radio counterparts were derived by taking the FIRST flux densities at an observed-frame frequency of 1.4 GHz and extrapolating to a rest-frame frequency of 5 GHz, assuming a radio power-law continuum of the form $f_\nu \propto \nu^{-0.5}$ (Rector et al. 2000). These flux densities were then divided by the flux densities from the $i$-band (AB7672) magnitudes taken from the Pâris et al. (2017) catalog and extrapolated to a rest-frame wavelength of 4400 Å, assuming an optical power-law continuum of the form $f_\nu \propto \nu^{-0.5}$ (Vanden Berk et al. 2001). Only 2 of the 17 radio counterparts were found to be radio-quiet; the other 15 were therefore culled from the comparison sample.

For the 149 L16 sources that do not have radio counterparts, we computed upper limits on their $R$ values as described above, except that the radio fluxes were derived by multiplying the rms radio flux at the SDSS position by a factor of 3. In order to meet our third criterion above and to ensure that only radio-quiet sources are considered for the comparison, we further excluded all sources that have upper limits on $R$ that are greater than 10. The final sample, hereafter the L16 comparison sample, includes 85 sources, 62 of which are at $z < 1.57$ (if, instead, we used a more conservative constraint on the radio-undetected sources, by multiplying their rms fluxes by a factor of 5, this would have reduced the sample size to 63 sources). Assuming the BAL quasar contamination fraction above, we can expect the L16 comparison sample to include not more than $\sim 1$ BAL quasar at $z < 1.57$. Figure 6 presents distributions of the redshift, luminosity, and number of pn counts for the L16 comparison sample.

L16 took a Bayesian approach to the X-ray spectral analysis, using the BNTORUS model. Unlike our analysis in the >2 keV rest-frame energy range, L16 fit their spectra in the

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18 This model includes an intrinsic power-law component and Compton scattering from absorbing material. When fitting unobscured quasars like those in our sample, the results of this model are in excellent agreement with those of the PEXRAV model in XSPEC (Magdziarz & Zdziarski 1995; see Brightman et al. 2015 for more details).
claimed best-fit Gaussian distribution for this histogram, and the hatched and solid black bars represent our radio-intermediate and radio-quiet WLQs, respectively.

**Figure 7.** Comparison of power-law photon indices measured in the observed-frame 0.5–8 keV between our WLQs and sources from the L16 comparison sample. The unshaded histogram represents the L16 comparison sample, the dashed curve is the best-fit Gaussian distribution for this histogram, and the hatched and solid black bars represent our radio-intermediate and radio-quiet WLQs, respectively.

**Table 4**

Best-fit Parameters of the L16 Sources with the Largest Number of Counts

| UXID (1)   | SDSS Name          | Observation ID (3) | z (4) | pn Counts (5) | $\Gamma_{0.5-8\text{ keV}}$ (from L16) (6) | $\Gamma_{0.5-8\text{ keV}}$ (from PEXRAV) (7) |
|-----------|-------------------|--------------------|------|---------------|------------------------------------------|------------------------------------------|
| N_38_68   | SDSS J021808.24−045845.2 | 0112371001         | 0.714| 3308          | 2.27 ± 0.02                              | 2.53 ± 0.09                              |
| N_38_117  | SDSS J021817.45−045112.5 | 0112371001         | 1.083| 1985          | 1.95 ± 0.03                              | 1.88 ± 0.09                              |
| N_20_50   | SDSS J022105.64−044101.5 | 0037982001         | 0.199| 974           | 2.11 ± 0.03                              | 2.16 ± 0.09                              |
| N_0_30    | SDSS J022224.20−034757.3 | 0604280101         | 1.687| 938           | 1.87 ± 0.07                              | 1.97 ± 0.15                              |
| N_113_13  | SDSS J022851.50−051223.1 | 0677590132         | 0.316| 619           | 2.13 ± 0.04                              | 2.17 ± 0.08                              |
| N_38_79   | SDSS J021830.59−045622.9 | 0112371001         | 1.397| 611           | 2.28 ± 0.05                              | 2.63 ± 0.35                              |

In nearly all cases, the measurement of an unrealistically high $\Gamma$ value is most likely a consequence of including a soft excess component in the spectral fitting. The distribution of the $\Gamma_{0.5-8\text{ keV}}$ values, as measured by L16, for the L16 comparison sample appears in Figure 7. In order to obtain a meaningful comparison between the L16 $\Gamma_{0.5-8\text{ keV}}$ values and the $\Gamma$ values of our WLQs, we re-fitted each of our objects in the observed-frame 0.5–8 keV range, this time with the Galactic absorbed power law and Compton reflection (PHABS+PEXRAV) model (a similar model with an additional intrinsic absorption component, zPHABS, was used for SDSS J0928+1848; see Section 2). We ran PEXRAV while fixing only the redshifts and the Galactic absorptions; all the other model parameters were free to vary. The best-fit $\Gamma_{0.5-8\text{ keV}}$ values resulting from these fits appear in Column (11) of Table 2.

The $\Gamma_{0.5-8\text{ keV}} = 4.51$ value for SDSS J1429+3859 appears to be unphysical, but can be explained by the indication of excess soft X-ray emission at <2 keV in the rest-frame (see Figure 2).

Furthermore, we searched for a potential systematic offset between the method L16 used to measure their $\Gamma_{0.5-8\text{ keV}}$ values and the analysis method we used to obtain the $\Gamma_{0.5-8\text{ keV}}$ values of our WLQs. Therefore, we have reanalyzed the XMM-Newton spectra of seven sources from the L16 comparison sample that had more than 600 total counts per source. Such a threshold on the number of counts ensures that we compare L16 data sets of roughly matched quality to those of our radio-quiet WLQs (see Table 1). We employed the same data reduction and analysis as described above on single L16 data sets of those seven sources; since each L16 source typically has 1–10 exposures per pointing, with a range of angular offsets from the aimpoint, we used the data set with the longest exposure time in each case. As done in L16, we restricted the fitting range to 0.5–8 keV in the observed-frame of each source, then fitted each data set once with a Galactic absorbed power law and Compton reflection (PHABS+PEXRAV) model and a second time with an added intrinsic absorption component (PHABS*zPHABS+PEXRAV); based on F-tests, none of the spectra warranted a neutral intrinsic absorption component. The results of this analysis are
given in Table 4. Column (1) gives the X-ray source identification string used by L16; columns (2) and (3) give the SDSS quasar name and corresponding XMM-Newton observation ID number, respectively; columns (4) and (5) give the redshifts and number of pn counts taken from L16, respectively; columns (6) and (7) give the \( \Gamma_{0.5-8\,\text{keV}} \) values from L16 and our PEXRAV analysis, respectively. We found no significant systematic difference between the L16 \( \Gamma_{0.5-8\,\text{keV}} \) values and the \( \Gamma_{0.5-8\,\text{keV}} \) values we obtained for these seven sources.\(^{20}\)

Similar to the analysis described in Section 2 for our WLQs, we also fitted those seven L16 sources with a Galactic absorbed power-law model and found a systematic offset of \( \approx+0.2 \) between \( \Gamma_{0.5-8\,\text{keV}} \) (PEXRAV) and \( \Gamma_{0.5-8\,\text{keV}} \) (power law), as may be expected, given that the PEXRAV model attempts to include an additional component due to reflection from neutral material. Additionally, we note that the seven L16 sources with the largest number of counts are not identical to those with the highest \( \Gamma_{0.5-8\,\text{keV}} \) values. Therefore, our results are not biased by the sources with the steepest spectral slopes. Figure 7 shows how the \( \Gamma_{0.5-8\,\text{keV}} \) values of our WLQs compare with those of the L16 comparison sample.

The \( \Gamma_{0.5-8\,\text{keV}} \) values of four of our WLQs, all of which are radio-quiet, lie above the 3\( \sigma \) threshold at the high end of the \( \Gamma_{0.5-8\,\text{keV}} \) distribution of the L16 comparison sample; similarly, the \( \Gamma_{0.5-8\,\text{keV}} \) value of another radio-quiet WLQ lies at the \( \sim2\sigma \) threshold. Importantly, the average \( \Gamma_{0.5-8\,\text{keV}} \) value of our six radio-quiet WLQs (\( \Gamma_{0.5-8\,\text{keV}} = 2.89^{+0.45}_{-0.30} \)) also lies above the \( 3\sigma \) threshold of the \( \Gamma_{0.5-8\,\text{keV}} \) distribution of the L16 comparison sample (this average drops to \( \Gamma_{0.5-8\,\text{keV}} = 2.28^{+0.57}_{-0.32} \) when SDSS J1429+3859 is excluded).

In order to check whether the \( \Gamma_{0.5-8\,\text{keV}} \) values of our WLQs, as a group, are significantly higher than those of typical quasars, we ran a Mann–Whitney nonparametric rank test between the \( \Gamma_{0.5-8\,\text{keV}} \) values of our six radio-quiet WLQs and those of the L16 comparison sample. We found that the two distributions are significantly different, with \( >99.8\% \) confidence (\( >3\sigma \)), one-tailed (another test with the exclusion of SDSS J1429+3859 resulted in the two distributions being significantly different with \( >99.5\% \) confidence). We also ran a similar Mann–Whitney test between the \( \Gamma_{0.5-8\,\text{keV}} \) distributions of our six radio-quiet and four radio-intermediate WLQs, and similarly found that the two distributions are significantly different at the 95\% confidence level. This result is also reflected in Table 3. The lower \( \Gamma \) values of the radio-intermediate WLQs, with respect to their radio-quiet counterparts, may be a manifestation of jet contributions to their X-ray emissions (e.g., Miller et al. 2011).

Our results therefore indicate that in the absence of potential X-ray emission from a jet along our line of sight, WLQs have significantly higher hard X-ray power-law photon indices than typical quasars. This result reinforces the idea that weak emission lines in quasars may be a direct consequence of a high Eddington fraction. In this respect, our results are in agreement with the Luo et al. (2015) model, which suggests that the scale height of the inner accretion disk grows as a function of the accretion rate and acts as a filter that prevents highly ionizing photons from reaching the BELR. However, in order to establish a relationship between BELR line strength and the Eddington fraction across wide ranges of these parameters, the hard X-ray power-law photon indices of a statistically meaningful sample of quasars should be measured accurately (see, e.g., Shemmer & Lieber 2015).

### 3.2. A Soft Excess—Accretion Rate Connection?

The discrepancies in the \( \Gamma \) values of our WLQs between those fitted in the \( >2\,\text{keV} \) rest-frame band and those in the observed-frame \( 0.5–8\,\text{keV} \) band (see Table 2) could be attributed to the existence of soft X-ray excess emission, at least in our lowest-redshift sources. The physical nature of this component is uncertain (Gierliński & Done 2004; Porquet et al. 2004; Vasudevan et al. 2014), yet it is present in many AGN spectra, which makes it of interest to search for the existence of this component in our sources. In order to check whether any of our sources show evidence for a soft excess, we extrapolated the best-fit Galactic absorbed power-law model (with added intrinsic neutral absorption for SDSS J0928+1848) obtained for rest-frame energies \( >2\,\text{keV} \) (see Section 2 and Table 2) to the \( >0.3\,\text{keV} \) observed-frame energies. All but one of our sources show \( \chi \) residuals no greater than the \( 3\sigma \) level and, therefore, no indication of excess soft X-ray emission. Only one of our WLQs, SDSS J1429+3859, has an indication of soft excess emission with \( \chi \) residuals up to \( 6\sigma \) (see Figure 2). This is our lowest-redshift WLQ. The non-detection of this feature in the other WLQs is not unexpected given their considerably higher redshifts and the \( \sim0.2\,\text{keV} \) energy threshold of XMM-Newton (see Shemmer et al. 2008).

In order to assess the effect of the putative soft excess on the photon index of SDSS J1429+3859, we performed an additional spectral fitting on this source in which a thermal component (the NLAPEC model in XSPEC) was added to the model employed in Section 3.1 (i.e., PHABS+PEXRAV+NLAPEC). This fitting resulted in a photon index value of \( \Gamma_{0.5-8\,\text{keV}} = 2.57^{+0.39}_{-0.68} \). An \( F \)-test shows that the addition of the NLAPEC component provides a significantly better fit, with \( >90\% \) confidence, and that the \( \Gamma_{0.5-8\,\text{keV}} \) value is reduced considerably with respect to the one from Section 3.1 (\( \Delta\Gamma_{0.5-8\,\text{keV}} \approx 2 \)).

A soft excess feature is expected to be more pronounced in sources with higher accretion rates (e.g., Done et al. 2012). The fact that we detect a feature of this kind in one of our radio-quiet sources is in agreement with the idea that WLQs have extremely high accretion rates. However, X-ray imaging spectroscopy of additional WLQs is required to establish such a connection.

### 3.3. Searching for Signatures of Compton Reflection and Iron-line Emission

We conducted a search for the existence of a Compton reflection continuum as well as signatures of a neutral narrow Fe K\( \alpha \) emission line at rest-frame 6.4\,keV in our WLQs in order to assess their potential effects on our photon index measurements. This was performed by fitting all the XMM-Newton spectra for each source in the \( >2\,\text{keV} \) rest-frame energy range with XSPEC, employing a Galactic absorbed power-law with a Compton reflection continuum model (i.e., the PEXRAV model in XSPEC, using a similar spectral fitting approach as the one performed in Section 3.1), and a Galactic
absorbed power law with a redshifted Gaussian emission-line model (ZGAUSS in XSPEC) for the Fe Kα emission line. The Gaussian rest-frame energy and width were fixed at $E = 6.4$ keV and $\sigma = 0.1$ keV, respectively. Table 5 lists the best-fit parameters from these fits. Column (1) gives the SDSS quasar name; column (2) gives the rest-frame EW of the Fe Kα emission line; column (3) gives the relative-reflection component ($R_{\text{rel}}$) of the Compton reflection continuum expressed as $R_{\text{rel}} = \Omega / 2 \pi$, where $\Omega$ is the solid angle subtended by the continuum source. Due to the relatively low quality of the SDSS J1012+5313 observation, this object was not included in this portion of the analysis.

Previous studies have shown trends where the EW of the narrow Fe Kα line decreases with X-ray luminosity, i.e., the “X-ray Baldwin effect” (e.g., Iwasawa & Taniguchi 1993; Ricci et al. 2013), the origin of which is still unclear. Table 5 shows that we have not detected any statistically significant Compton reflection continua nor any neutral Fe Kα emission in any of our sources. Due to the relatively high luminosities of our sources, these results are in agreement with the X-ray Baldwin effect. However, our results can be referred to as not being sensitive enough to either confirm or rule out an X-ray Baldwin Effect. Detection of (or placement of meaningful constraints on) narrow iron lines in such luminous quasars requires considerably longer exposures with XMM-Newton.

### 3.4. X-Ray Variability

Table 2 shows that no unusual X-ray variations are observed for any of our WLQs between their Chandra and XMM-Newton epochs, separated by $\approx 1$ year in the rest-frame of each source. The differences between each pair of $\alpha_{\text{ox}}$ values indicates X-ray variations of up to a factor of $\approx 3.5$ (in SDSS J1447−0203), which is consistent with the X-ray variability of typical quasars having similar luminosities (e.g., Vagnetti et al. 2013; Lanzuisi et al. 2014). Therefore, we do not expect that our main results are affected by X-ray variability.

### 4. Summary

We present X-ray spectroscopy of 10 SDSS X-ray normal WLQs at $0.928 \leq z \leq 3.767$ that have sufficient X-ray counts to allow basic measurements of their X-ray spectra with XMM-Newton observations. Six of these are radio-quiet and four are radio-intermediate. Our analysis provides measurements of the hard X-ray photon index in these sources. We have compared these data with similar data for a carefully selected sample of 85 radio-quiet type 1 quasars in order to quantify the extremity of the hard X-ray spectral slopes of WLQs with respect to typical quasars. The results of this comparison show that the photon indices of radio-quiet WLQs, as a group, constitute the $\geq 3 \sigma$ tail of the photon index distribution in quasars. The radio-intermediate WLQs have considerably lower photon indices that are comparable to those of the bulk of the quasar population; we suggest that X-ray emission from a jet contributes to the harder X-ray spectra in these sources. Considering the hard X-ray power-law photon index as an Eddington fraction indicator, our results imply that radio-quiet WLQs occupy the extreme high end of the accretion-rate distribution in quasars.

Our lowest-redshift radio-quiet WLQ, SDSS J1429+3859, is our only source that exhibits soft excess emission, which may be another manifestation of its high accretion rate. None of our sources show signatures of Compton reflection, or the presence of a narrow iron line, and none show unusual X-ray variability. These results are in line with the high luminosity of our sources.

In the near future, a more rigorous comparison with the $\Gamma$ values of our WLQs could be made using recent and deeper XMM-Newton observations of a subset of the L16 comparison sample (Chen et al. 2018). The new spectra of these sources will also be fitted at the $>2$ keV rest-frame range to conform with the spectral fitting of our WLQs. Sensitive X-ray imaging spectroscopy of a large sample of quasars across a wide range of BELR line strength, redshift, and luminosity, is required for establishing connections between BELR line strength, Eddington fraction, and the prominence of a soft excess component in all quasars.

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