On the Fraction of X-Ray-weak Quasars from the Sloan Digital Sky Survey

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Abstract

We investigate systematically the X-ray emission from type 1 quasars using a sample of 1825 Sloan Digital Sky Survey non-broad absorption line (non-BAL) quasars with Chandra archival observations. A significant correlation is found between the X-ray-to-optical power-law slope parameter ($\alpha_{OX}$) and the 2500 Å monochromatic luminosity ($L_{2500\AA}$), and the X-ray weakness of a quasar is assessed via the deviation of its $\alpha_{OX}$ value from that expected from this relation. We demonstrate the existence of a population of non-BAL X-ray-weak quasars, and the fractions of quasars that are X-ray weak by factors of $\geq 6$ and $\geq 10$ are 5.8% ± 0.7% and 2.7% ± 0.5%, respectively. We classify X-ray-weak quasars (X-ray weak by factors of $\geq 6$) into three categories based on their optical spectral features: weak emission-line quasars (WLQs; C IV rest-frame equivalent width $< 16$ Å), red quasars ($\Delta(g−i) > 0.2$), and unclassified X-ray-weak quasars. The X-ray-weak fraction of $35^{+12}_{−9}$% within the WLQ population is significantly higher than that within non-WLQs, confirming previous findings that WLQs represent one population of X-ray-weak quasars. The X-ray-weak fraction of $13^{+15}_{−2}$% within the red quasar population is also considerably higher than that within the normal quasar population. The unclassified X-ray-weak quasars do not have unusual optical spectral features, and their X-ray weakness may be mainly related to quasar X-ray variability.

Unified Astronomy Thesaurus concepts: Galaxy nuclei (609); X-ray quasars (1821); Active galaxies (17)

Supporting material: machine-readable tables

1. Introduction

X-ray emission is an ubiquitous property of active galactic nuclei (AGNs). Extragalactic X-ray surveys with Chandra and XMM-Newton have provided a quite complete understanding of the distant AGN population (see Brandt & Alexander 2015 for a review). AGN X-ray emission has been found to be strongly correlated with the optical/UV emission (e.g., Avni & Tananbaum 1982, 1986). It is believed that AGN optical/UV photons are emitted from the accretion disk, and X-ray continuum emission arises from inverse Compton scattering of these optical/UV photons in a hot accretion-disk “corona” (e.g., Galeev et al. 1979; Reynolds & Nowak 2003; Jiang et al. 2014). The X-ray-to-optical power-law slope parameter $\alpha_{OX}$, conventionally defined as $\alpha_{OX} = 0.3838 \log (L_{2keV}/L_{2500\AA})$ (Tananbaum et al. 1979),9 is commonly used to quantify the ratio between the X-ray and optical/UV luminosity of AGNs. Studies of the X-ray and optical/UV emission of large AGN samples have established a significant $\alpha_{OX}−L_{2500\AA}$ anticorrelation spanning a broad range in $L_{2500\AA}$ and redshift (e.g., Vignali et al. 2003; Strateva et al. 2005; Steffen et al. 2006; Just et al. 2007; Lusso et al. 2010; Lusso & Risaliti 2016; Chiaraluce et al. 2018), providing fundamental constraints on disk–corona models for AGNs.

The empirical $\alpha_{OX}−L_{2500\AA}$ relation also allows identification of unusual X-ray-weak AGNs (especially X-ray-weak type 1 quasars), showing X-ray emission significantly weaker than that expected from the $\alpha_{OX}−L_{2500\AA}$ relation. The nearby ($z = 0.192$) narrow-line type 1 quasar PHL 1811 is the best-studied example of this class (Leighly et al. 2007a). The X-ray luminosity of PHL 1811 is a factor of $\sim30$–100 times weaker than that expected from the $\alpha_{OX}−L_{2500\AA}$ relation. The steep X-ray spectrum (with photon index $\Gamma = 2.3 \pm 0.1$), lack of evidence for intrinsic X-ray and UV absorption, and short-term X-ray flux variability by a factor of $\sim5$ strongly suggest that PHL 1811 is intrinsically X-ray weak (Leighly et al. 2007a). The optical/UV line emission of PHL 1811 is also unusual (e.g., no forbidden or semiforbidden lines, very strong Fe II and Fe III, unusual very low-ionization lines, and very weak high-ionization lines; see Leighly et al. 2007b). Its C IV emission line is blueshifted and asymmetric, and it has a rest-frame equivalent width (REW) of only 6.6 Å, about five times smaller than that in the composite quasar spectrum (Vanden Berk et al. 2001).

Except for a few candidates for intrinsically X-ray-weak quasars (e.g., Gallagher et al. 2001; Wu et al. 2011; Luo et al. 2013, 2014; Liu et al. 2018) like PHL 1811, X-ray weakness in type 1 quasars is generally ascribed to absorption. Broad absorption line (BAL) quasars are well known to be X-ray weak compared to quasars with normal optical/UV spectra (e.g., Green & Mathur 1996; Brandt et al. 2000; Gallagher et al. 2006). Approximately one in every six optically selected quasars shows BALs in its rest-frame UV spectra (e.g., Reichard et al. 2003; Gibson et al. 2009b). Spectroscopic X-ray studies have found that BAL quasars typically have underlying X-ray continua similar to those of normal quasars (Gallagher et al. 2002) and the X-ray-weakest BAL quasars...
tend to have the hardest X-ray spectra (Gallagher et al. 2006), suggesting that the X-ray weakness in BAL quasars is primarily due to absorption.

There is a small population of weak emission-line quasars (WLQs; e.g., Diamond-Stanic et al. 2009; Shenmer et al. 2009; Plotkin et al. 2010a; Laor & Davis 2011; Wu et al. 2012) that are often known to show weak X-ray emission. They have broad UV emission lines (e.g., C IV λ1549) that are significantly weaker than those of normal quasars. Studies of large samples of this class of objects have found that a large fraction (≥50%) of WLQs are X-ray weak (Wu et al. 2012; Luo et al. 2015; Ni et al. 2018). The small effective power-law photon index (Γ_{eff} ≈ 1.2) measured from X-ray stacking analyses indicates that the X-ray-weak WLQs are on average likely X-ray absorbed (e.g., with N_H ≈ 9 × 10^{23} cm^{-2}; Luo et al. 2015).

Few studies have investigated systematically the populations of X-ray-weak quasars. Gibson et al. (2008a) analyzed the X-ray and UV properties of 536 Sloan Digital Sky Survey (SDSS; York et al. 2000) quasars, including 315 with Chandra coverage and 221 with XMM-Newton coverage. Based on 139 RQ non-BAL quasars in sample B of Gibson et al. (2008a), their results showed that X-ray-weak quasars are rare. Limited by their sample size, however, they only measured upper limits on the fraction of type 1 quasars with a given factor of X-ray weakness (Figure 5 of Gibson et al. 2008a).

Motivated by the significantly increased numbers of SDSS quasars and Chandra observations since the Gibson et al. (2008a) work, we present here a systematic and uniform X-ray study of 1825 quasars with Chandra coverage, which are drawn from the SDSS Seventh Data Release (DR7; Abazajian et al. 2009) and Tenth Data Release (DR10; Ahn et al. 2014). Using the updated optical/UV and X-ray data, we can not only constrain better the fraction of X-ray-weak quasars, but also attempt to classify the causes for their X-ray weakness. Studies of the fraction and nature of these populations of exceptional objects may provide insights into the disk–corona system and nuclear obscuring material for accreting supermassive black holes (SMBHs). We describe our sample selection and X-ray data analysis in Sections 2 and 3, respectively. The results, including the X-ray and optical/UV properties, and the fraction of X-ray-weak quasars, are presented in Section 4. In Section 5, we discuss the nature of quasar X-ray weakness. We summarize in Section 6. Throughout this work, we use J2000 coordinates and a cosmology with \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_M = 0.3 \), and \( \Omega_{\Lambda} = 0.7 \) (e.g., Spergel et al. 2007).

2. Sample Selection

2.1. SDSS and Chandra Archive Selection

The SDSS DR7 quasar catalog (Schneider et al. 2010) contains 105,783 bona fide quasars in the redshift range \( 0.065 < z < 5.460 \) that have luminosities brighter than \( M_1 = -22.0 \) and have at least one broad emission line with FWHM larger than 1000 km s\(^{-1}\) or have interesting/complex absorption features. The SDSS DR10 quasar catalog (Pâris et al. 2014) contains 166,583 Baryon Oscillation Spectroscopic Survey (BOSS) objects that have luminosities \( M_1 < -20.5 \) and either have at least one emission line with FWHM larger than 500 km s\(^{-1}\) or have interesting/complex absorption features.

We selected DR7 and DR10 quasars in the redshift range \( 1.700 < z < 2.700 \). The lower limit on the redshift ensures that the full velocity range up to 29,000 km s\(^{-1}\) shortward of the C IV λ1549 emission line is redshifted into the SDSS and BOSS spectra, allowing unambiguous identification of BAL quasars from their broad C IV absorption. The upper limit on the redshift ensures that the effective wavelengths (rest frame \( \geq 2000 \text{ Å} \)) of the absolute \( i \)-band magnitudes, which are extrapolated to derive the rest-frame 2500 Å flux densities (Section 2.3 below), do not deviate much from 2500 Å. We then searched the Chandra archive to find Advanced CCD Imaging Spectrometer (Garmire et al. 2003) observations (with no gratings) that were public as of 2016 July 1 and have pointing positions within 17' of the selected sources. We used the FIND_CHANDRA_OBSDID script in Chandra Interactive Analysis of Observations (CIAO)\(^{10}\) to check if these sources are actually covered by Chandra,\(^{11}\) resulting in a parent sample of 2475 SDSS quasars with 1472 Chandra observation IDs.\(^{12}\)

2.2. Excluding BAL Quasars

It is necessary to exclude BAL quasars to avoid quasars with possible strong X-ray absorption. The Shen et al. (2011) DR7 quasar catalog lists a BAL_flag parameter indicating the identification of BAL quasars. This parameter flags both the objects in the SDSS Fifth Data Release (DR5) BAL quasar catalog (Gibson et al. 2009b) and the visually confirmed post-DR5 BAL quasars. The Pâris et al. (2014) DR10 quasar catalog lists a BAL_FLAG_VI parameter flagging those visually confirmed BAL quasars and also a BAL C IV parameter indicating traditional BAL quasars (Weymann et al. 1991). We consider a DR7 quasar with BAL_flag > 0 in the Shen et al. (2011) catalog or a DR10 quasar with BAL_FLAG_VI = 1 or BAL C IV > 0 in the Pâris et al. (2014) catalog a BAL quasar. In our parent sample, 345 quasars satisfy one or more of these criteria, and they were thus excluded.

The B10 definition adopted by Gibson et al. (2009b) and the BI definition adopted by Pâris et al. (2014) both apply a conservative absorption trough width threshold of 2000 km s\(^{-1}\). This threshold may miss relatively weak BAL features. Therefore, we adopted the absorption index (AI; e.g., Trump et al. 2006) parameter to search for additional BAL quasars. It was computed as

\[
AI \equiv \int_{0}^{29,000} (1 - f(v))C dv, \tag{1}
\]

where \( f(v) \) is the continuum-normalized flux density. The value of \( C \) is initially set to zero; it is set to 1 whenever \( f(v) \) has been continuously less than 0.9 for more than 1000 km s\(^{-1}\). A sample object with AI > 0 is also considered a BAL quasar.

We fitted the SDSS and BOSS spectra of our sample quasars following the method of Gibson et al. (2008b), which we summarize briefly here. For each sample quasar, we corrected its spectrum for Galactic extinction using the reddening curve of Cardelli et al. (1989) and O'Donnell (1994). The continuum was fitted by a power law with Small Magellanic Cloud reddening (Pei 1992); the continuum regions were selected to be rest-frame 1250–1350, 1600–1800, 1950–2050, 2150–2250,

\(^{10}\) See http://cxc.cfa.harvard.edu/ciao/ for details.

\(^{11}\) If a source has multiple Chandra observations, we selected the observation with the longest exposure and the smallest off-axis angle. Sources that lie within 32 pixels of any chip edge were excluded.

\(^{12}\) There are 610 Chandra pointings that have two or more quasars within the field.
and 2950–3700 Å, which are free from strong emission and absorption features. We iteratively fitted the continuum regions with a $3\sigma$ clipping method (i.e., spectral bins that deviate from the continuum model by more than $3\sigma$ were ignored at each iteration, with $\sigma$ being the spectral error). The continuum was determined using the three best-fit parameters: power-law normalization, spectral index $\alpha$, and reddening $E(B - V)$. Because the spectral index $\alpha$ and reddening $E(B - V)$ are degenerate, the $E(B - V)$ value derived from the fitting is not necessarily attached to any physical significance. Thus, the continuum is not corrected for any intrinsic reddening. To identify C IV BAL features, we smoothed the SDSS or BOSS spectrum using a 3 pixel boxcar and computed the AI parameter. For a quasar that has both SDSS and BOSS spectra, we consider it a BAL quasar if either of its spectra has AI > 0. Using this criterion, 173 additional BAL quasars were excluded, leaving us with 1957 quasars in the parent sample.

2.3. Measuring $f_{2500\AA}$

The measurement of the flux density at rest-frame 2500 Å ($f_{2500\AA}$) is key to our analyses. In this paper, we derived the $f_{2500\AA}$ values from the 2500 Å luminosities, which were converted from the absolute $i$-band magnitudes $M_i(z = 2)$ using Equation (4) of Richards et al. (2006). The $M_i(z = 2)$ values were adopted from the Shen et al. (2011) DR7 and Pâris et al. (2014) DR10 quasar catalogs. Because the absolute flux calibration errors in the BOSS spectra are relatively large and wavelength dependent (e.g., Pâris et al. 2012; Margala et al. 2016), we chose to estimate the $f_{2500\AA}$ values from $M_i(z = 2)$ instead of from spectral fitting for both SDSS DR7 and BOSS DR10 quasars to ensure homogeneous flux measurements.

We compared our $f_{2500\AA}$ values for the DR7 quasars in our final sample (see Section 2.5 below) to those reported in the Shen et al. (2011) catalog. The Shen et al. (2011) $f_{2500\AA}$ values, which were measured from spectral fitting, are largely consistent with our $f_{2500\AA}$ values, with a mean $f_{2500\AA}/f_{2500\AA}$,Shen value of 0.99 and a standard deviation of 0.35. In addition, we verified that our $f_{2500\AA}$ values are consistent with those ($f_{2500\AA,spec}$) derived from our continuum fitting results in Section 2.2 (i.e., using power-law normalization, spectral index $\alpha$, and reddening $E(B - V)$) for the DR7 quasars in our final sample, with a mean $f_{2500\AA}/f_{2500\AA,spec}$ value of 0.98 and a standard deviation of 0.28. We note that because the photometry and spectra are taken at different times, some of the standard deviation may just be due to quasar variability (rather than our methodological errors). For the DR10 quasars in our final sample (having BOSS spectra), we identified small wavelength-dependent calibration offsets between the photometric magnitudes and the spectrum synthesized magnitudes (e.g., Margala et al. 2016), indicating that any flux density measurements from the continuum fitting results in Section 2.2 may be unreliable.13

2.4. Excluding RL Quasars

We also need to exclude radio-loud (RL) quasars, as they are well known to have X-ray emission levels systematically higher than those of radio-quiet (RQ) quasars with comparable optical/UV luminosities (e.g., Zamorani et al. 1981; Worrall et al. 1987). X-ray emission related to the jet, in addition to enhanced emission from the accretion-disk corona, may be required to interpret the X-ray excess of RL quasars (Miller et al. 2011; Zhu et al. 2020). Following Jiang et al. (2007), we matched the remaining sample of 1957 quasars to the latest Faint Images of the Radio Sky at Twenty-cm (FIRST; Becker et al. 1995) survey catalog (14Dec17 version)14 with a matching radius of 30″. We classified objects that have only one radio component within 5″ as core-dominated quasars and objects that have multiple radio components within 30″ as lobe-dominated quasars. The sample contains 99 FIRST-detected quasars, including 80 core-dominated quasars and 19 lobe-dominated quasars. For each FIRST-detected object, we used the integrated flux density listed in the FIRST catalog to calculate its 1.4 GHz flux. For each lobe-dominated quasar, the total radio flux was calculated using all of its radio components within 30″. We visually examined the quasar optical image from the Digital Sky Survey (DSS) to ensure that its radio components are not associated with any interloper. We also matched the 50 quasars that lie outside the FIRST survey area to the NRAO Very Large Array (VLA) Sky Survey (NVSS; Condon et al. 1998). Three objects have one NVSS source matched within 30″. The upper limits on the 1.4 GHz fluxes for FIRST-undetected objects were set to 0.25 + $3\sigma_{rms}$ mJy, where 0.25 is the CLEAN bias correction and $\sigma_{rms}$ is the median rms noise of the FIRST survey (0.14; White et al. 1997); the upper limits on the 1.4 GHz fluxes for NVSS-undetected objects were set to 1.35 mJy, corresponding to three times the typical rms noise of the NVSS.

The radio-loudness parameter is defined as $R = f_{5GHz}/f_{2500\AA}$ (e.g., Stocke et al. 1992), where $f_{5GHz}$ is the flux density at rest-frame 5 GHz. The $f_{5GHz}$ values (or their upper limits) were converted from the observed 1.4 GHz flux densities assuming a radio power-law slope of $\alpha = -0.5$. The FIRST survey is not sufficiently sensitive to discriminate $R \geq 10$ versus $R < 10$ for a large fraction of our sample objects, and we therefore classify objects with $R \geq 100$ as RL, objects with $10 \leq R < 100$ as radio intermediate (RI), and objects with $R < 10$ as RQ. There are 413 RQ, 30 RI, and 59 RL quasars within the remaining sample. Another 1455 objects with upper limits on $R$ larger than 10 are referred to as radio unclassified (RU), 97 of which have upper limits on $R$ larger than 100. We excluded the 59 RL quasars, leaving 1898 objects in our sample.

2.5. Final Sample

After excluding the BAL and RL quasars from the parent sample, we also removed 73 quasars that are Chandra targets; these X-ray targets might have unusual X-ray properties, and they may bias our systematic investigation of X-ray-weak quasars. The final sample contains 1825 quasars, and we refer to this sample as sample A. A summary of the sample selection is presented in Table 1. Sample A contains 555 DR7 quasars and 1270 DR10 quasars,15 and we show in Figure 1 the 1825 sample A objects together with all the SDSS DR7 and DR10 quasars in the redshift versus absolute $i$-band magnitude $M_i(z = 2)$ plane.

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13 We note that such small calibration errors hardly affect the computations of the AI parameters in Section 2.2 or the BI parameters in Pâris et al. (2014), and thus we do not consider the BAL quasar exclusion unreliable.

14 http://sundog.stsci.edu/

15 There are 137 quasars in sample A that are in both the DR7 and DR10 quasar catalogs. We refer to these quasars as DR7 quasars, and we preferentially adopt their properties from the DR7 catalog.
The X-ray observations for the sample A quasars are listed in Table 2. The measured $f_{2500\AA}$ and $R$ values (or their upper limits; see Section 2.4), along with the absolute $i$-band magnitudes $M_i$, REWs of the C IV $\lambda 1549$ emission, and relative $g-i$ colors (i.e., $\Delta(g - i)$; e.g., Richards et al. 2003) derived from the SDSS DR7 and DR10 quasar catalogs for the sample A objects are listed in Table 3. Properties from the SDSS DR7 quasar catalog are preferred when a quasar has an entry in both catalogs. We listed the C IV REW and $\Delta(g - i)$ values, because weak C IV emission lines and red $\Delta(g - i)$ colors are probably related to quasar X-ray weakness (see Sections 5.2.1 and 5.2.2 for further discussion). There are 31 DR10 quasars in sample A that have C IV $\lambda 1549$ REW values of $-1$ in the catalog, indicating that a principal component analysis failed to fit the emission line (Pâris et al. 2014). For each of these objects, we fitted a power-law local continuum between rest-frame 1450–1470 and 1650–1820 Å, and then measured the C IV REW between 1500 and 1600 Å (see Section 7.3 of Pâris et al. 2012). The C IV REW values of these 31 DR10 quasars range from 0.9 to 479.1 Å, with a median value of 33.8 Å and a mean value of 84.5 Å. 16

3. X-Ray Data Analysis

X-ray data reduction was performed using CIAO version 4.8 and CALDB version 4.7.0. For each observation ID, we reprocessed the Chandra data set using the CHANDRA_REPRO script. Background flares were removed using the DEFLARE script with an iterative 3σ clipping method.

We made for each of the 1825 sample objects X-ray images in the 0.5–7 keV (broad), 0.5–2 keV (soft), and 2–7 keV (hard) bands from the cleaned level 2 event file. X-ray source detection was performed on the images using the WAVDETECT (Freeman et al. 2002) script with wavelet scales of 1, 1.414, 2, 2.828, 4, 5.656, and 8 pixels, and a significance threshold of $10^{-6}$. If a sample object is detected by WAVDETECT within 3σ of the SDSS position, we used the WAVDETECT threshold as its X-ray position; otherwise, we used the SDSS astrometry as the X-ray position. Aperture photometry was performed to extract source counts in the broad, soft, and hard bands. We used circular and annular regions centered at the X-ray position to extract source and background counts, respectively. The radius of the circle was chosen to enclose 90% of the point-spread function at 1 keV, while the inner and outer radii of the annulus were chosen to be the source radius plus 15 and 50 pixels, respectively. We visually inspected the background-extraction region for each sample object. In cases where any WAVDETECT contaminates the background region, we excluded its elliptical WAVDETECT region that contains the majority of the source counts from the annulus. We manually changed the annulus to a pie-shaped region whenever the background region is partially off chip.

To assess the detection significance, we calculated in each of the broad, soft, and hard bands a binomial no-source probability $P_B$ using the following equation (e.g., Xue et al. 2011; Luo et al. 2013, 2015):

$$P_B(X \geq S) = \sum_{x=S}^{N} \frac{N!}{x!(N-x)!} p^x (1-p)^{N-x},$$

where $S$ is the total number of counts in the source-extraction region; $N = S + B$, where $B$ is the total number of counts in the background-extraction region; $p = 1/(1 + \text{BACKSCAL})$, where BACKSCAL is the background-to-source area ratio. If a sample object satisfied $P_B < 0.01$ in one band, we consider it detected in this band and calculated net counts along with associated 1σ errors, derived from 1σ errors (Gehrels 1986) on the source and background counts; otherwise we consider it undetected in this band and calculated a 3σ confidence level upper limit on the source counts using the Bayesian method of Kraft et al. (1991). We consider a source X-ray detected if it is detected in one or more of the three X-ray bands. Our sample A

16 Adopting the same method, our measurements of the C IV REWs for other DR10 quasars in sample A are generally consistent with the C IV REWs reported in the Pâris et al. (2014) DR10 quasar catalog.

17 See https://cxc.cfa.harvard.edu/ciao/ahelp/dmregions.html for a description of the pie-shaped region.
Table 2
Chandra Observations and X-Ray Photometric Properties

| SDSS Name (J2000) | Data Release | Redshift | Observation ID | Exposure Time (ks) | Broad Band (0.5–7 keV) | Soft Band (0.5–2 keV) | Hard Band (2–7 keV) | Band Ratio | $\Gamma_{\text{eff}}$ | Sample B | Sample C |
|-------------------|--------------|----------|----------------|-------------------|------------------------|----------------------|---------------------|------------|----------------|----------|----------|
| 000015.47+005246.8 | 7            | 1.8571   | 11591          | 21.7              | 61.5$^{+6.7}_{-6.6}$  | 40.1$^{+2.7}_{-2.6}$ | 21.4$^{+5.3}_{-5.6}$ | 0.53$^{+0.18}_{-0.15}$ | 1.6$^{+0.7}_{-0.3}$ | 0        | 0        |
| 000018.18+050803.6 | 10           | 2.2279   | 7334           | 2.7               | <8.3                   | <8.7                 | <5.9                | ...        | 1.8          | 0        | 0        |
| 000029.98+004845.3 | 10           | 2.4120   | 11591          | 21.2              | 11.3$^{+1.3}_{-1.2}$  | 6.8$^{+3.4}_{-3.3}$  | 18.6               | 0.79$^{+1.0}_{-0.6}$ | 1.1$^{+0.6}_{-1.0}$ | 0        | 0        |
| 000106.87+023845.9 | 10           | 1.7600   | 4837           | 5.0               | 4.5$^{+3.4}_{-3.3}$   | 4.7$^{+3.4}_{-3.3}$  | <5.9               | 0.15$^{+0.22}_{-0.14}$ | 2.6$^{+2.0}_{-0.9}$ | 0        | 0        |
| 000159.88+003715.5 | 10           | 2.3910   | 4861           | 4.8               | <16.7                  | <13.2               | <11.3              | ...        | 1.8          | 0        | 0        |

**Note.** Columns (1)–(3): SDSS name in the J2000 equatorial coordinate format, SDSS data release number, and redshift. The improved redshifts from Hewett & Wild (2010) reported in the Shen et al. (2011) catalog are listed for the DR7 quasars. Column (4): Chandra observation ID. Column (5): Chandra effective exposure time in the broad (0.5–7 keV) band. Columns (6)–(8): broadband (0.5–7 keV), soft-band (0.5–2 keV), and hard-band (2–7 keV) net counts in the source region. A 3$\sigma$ confidence level upper limit on the source counts is given if the source is undetected. Column (9): band ratio between the hard-band and soft-band counts. An entry of "..." indicates that the source is undetected in both bands. Column (10): 0.5–7 keV effective power-law photon index derived from the band ratio. It is fixed at 1.8 for any source that is undetected in both the soft and hard bands (see Section 3). Columns (11) and (12): an entry of "1" indicates that the object is in sample B or sample C (see Section 4.3). Table 2 is sorted by increasing J2000 R.A. and is published in its entirety in machine-readable format. A portion is shown here for guidance regarding its form and content. (This table is available in its entirety in machine-readable form.)
Table 3

X-Ray and Optical Properties

| SDSS Name              | \(M_i\) | \(f_{2\text{keV}}\) | \(F_{0.5-7\text{keV}}\) | \(\log L_{2-10\text{keV}}\) | \(f_{2500\text{Å}}\) | \(\alpha_{\text{OX}}\) | \(\Delta\alpha_{\text{OX}}\) | \(f_{\text{weak}}\) | \(\text{REW C IV}\) | \(\Delta(g - i)\) | \(R\) | X-ray Weak |
|-----------------------|---------|---------------------|-------------------------|---------------------------|------------------|-----------------|----------------------------|------------------|------------------|-----------------|------|-----------|
| 000015.47+005246.8    | -26.19  | 6.36                | 4.26                    | 44.75                     | 0.52             | -1.50           | 0.00                       | 1.0              | 44.1             | 0.131           | <12.0| 0         |
| 000018.18+050803.6    | <25.75  | <10.85              | <5.40                   | <45.06                    | 0.25             | <1.29           | <0.17                     | >0.4             | 57.0             | 0.056           | <26.5| 0         |
| 000029.98+004845.3    | -24.43  | 0.74                | 0.91                    | 44.22                     | 0.06             | -1.51           | -0.17                     | 2.7              | 78.9             | 0.047           | <106.0| 0         |
| 000106.87+023845.9    | -23.98  | 2.92                | 0.82                    | 44.03                     | 0.07             | -1.31           | -0.00                     | 1.0              | 51.6             | <0.085          | <82.5| 0         |
| 000159.88+003715.5    | -24.88  | <9.55               | <4.57                   | <45.06                    | 0.10             | <1.16           | <0.23                     | >0.3             | 43.4             | <0.031          | <68.9| 0         |

Note. Columns (1) and (2): SDSS name in the J2000 equatorial coordinate format and absolute \(i\)-band magnitude. Column (3): rest-frame 2 keV flux density in units of \(10^{-32} \text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}\). A 3\(\sigma\) confidence level upper limit on \(f_{2\text{keV}}\) is given if the source is undetected. Columns (4) and (5): observed-frame 0.5–7 keV flux in units of \(10^{-14} \text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}\) and logarithm of the rest-frame 2–10 keV luminosity in units of erg s\(^{-1}\), both calculated using \(f_{2\text{keV}}\) and \(\Gamma_{\text{eff}}\) (see Table 2). Column (6): rest-frame 2500 Å flux density in units of \(10^{-22} \text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}\). Column (7): measured X-ray-to-optical power-law slope \(\alpha_{\text{OX}}\). A 3\(\sigma\) confidence level upper limit on \(\alpha_{\text{OX}}\) is given if the source is undetected. Column (8): difference between the measured \(\alpha_{\text{OX}}\) and that expected from our best-fit \(\alpha_{\text{OX}} - L_{2500\text{Å}}\) relation. Column (9): X-ray-weakness factor measured from \(\Delta\alpha_{\text{OX}}\). Column (10): REW (in units of angstroms) of the C IV \(\lambda 1549\) emission line. Column (11): relative \(g - i\) color. Column (12): radio-loudness parameter. Column (13): an entry of “1” indicates that the object is X-ray weak. We adopted \(\Delta\alpha_{\text{OX}} = -0.3\) to be the threshold separating X-ray-normal and X-ray-weak quasars (see Section 4.2). Table 3 is sorted by increasing J2000 R.A. and is published in its entirety machine-readable format. A portion is shown here for guidance regarding its form and content.

(This table is available in its entirety in machine-readable form.)
contains 1344 X-ray-detected and 481 X-ray-undetected quasars. Figure 2 shows the distributions of the broadband effective exposure times and off-axis angles for these X-ray-detected and X-ray-undetected objects. The effective exposure time is the exposure time that has been corrected for the effects of vignetting and CCD gaps. The X-ray-detected quasars in general have longer exposures and smaller off-axis angles than the X-ray-undetected quasars. The numbers of detected/undetected DR7/DR10 quasars in specific X-ray bands are listed in Table 4.

Assuming power-law X-ray spectra modified by Galactic absorption, we derived the effective power-law photon indices ($\Gamma_{\text{eff}}$) from the band ratios for the 1285 sample objects that are detected in at least one of the soft and hard bands. The band ratio is defined as the ratio between the hard-band and soft-band counts. For each of the 732 objects that are detected in both the soft and hard bands, the band ratio was calculated by dividing the hard-band net counts by the soft-band net counts, and its associated 1σ uncertainties were derived using the method of Bayesian estimation of hardness ratios (BEHR; Park et al. 2006). For each of the 553 objects that are detected in only one of the soft and hard bands, we adopted the band ratio to be the mode of its posterior probability distribution computed using BEHR (Park et al. 2006). These are best-guess estimates, and they appear more appropriate for deriving source fluxes than assuming a fixed spectral shape (Luo et al. 2017). To derive $\Gamma_{\text{eff}}$ from the band ratio, we used the CIAO SPECEXTRACT script to create the source spectrum, auxiliary response file, and redistribution matrix file. We then used the Sherpa (CIAO’s modeling and fitting package; e.g., Freeman et al. 2001) FAKE_PHA command to create simulated spectra for a power-law plus Galactic absorption model with varying $\Gamma_{\text{eff}}$. The observed band ratio was compared to the modeled band ratios, and the value of $\Gamma_{\text{eff}}$ was determined by interpolating the modeled $\Gamma_{\text{eff}}$ values.

For each of the 540 quasars that are undetected in both the soft and hard bands (including 59 objects detected only in the broad band), the band ratio is not available; thus, we adopted a fixed $\Gamma_{\text{eff}}$ value of 1.8, which is around the median value of $\Gamma_{\text{eff}}$ for sample A objects (see Section 4.1 below). Among the 540 quasars with fixed $\Gamma_{\text{eff}}$ values, there are three X-ray-detected (i.e., detected only in the broad band) objects having $\Delta \alpha_{\text{OX}} \leq -0.3$ and one X-ray-undetected object having an upper limit on $\Delta \alpha_{\text{OX}} \leq -0.3$; these four objects are considered X-ray weak (see Section 4.2 below). Because the detected X-ray-weak quasars have a median $\Gamma_{\text{eff}}$ value of 0.8 (see Section 4.2 below), these four quasars likely have smaller $\Gamma_{\text{eff}}$ values. However, as their number is small, and they may also

### Table 4

| X-ray Detection Breakdown                     | Sample A | Sample B | Sample C |
|-----------------------------------------------|----------|----------|----------|
|                                               | DR7      | DR10     | All      | DR7      | DR10     |
| Detected in the Broad Band                    | 473      | 806      | 1279     | 216      | 207      |
| Detected in the Soft Band                     | 475      | 781      | 1256     | 214      | 198      |
| Detected in the Hard Band                     | 321      | 440      | 761      | 179      | 158      |
| Detected in Both the Soft and Hard Bands      | 317      | 415      | 732      | 177      | 155      |
| Detected in Only One of the Soft and Hard Bands| 162      | 391      | 553      | 39       | 46       |
| X-ray Detected                               | 490      | 854      | 1344     | 218      | 208      |
| X-ray Undetected                              | 65       | 416      | 481      | 0        | 0        |

Note. We consider a source X-ray detected if it is detected in at least one of the three X-ray bands and consider a source X-ray undetected if it is undetected in all three X-ray bands. All objects in samples B and C are X-ray detected.
be intrinsically X-ray-weak quasar candidates, we still chose to adopt $\Gamma_{\text{eff}} = 1.8$ to calculate the relevant parameters (or their upper limits); adopting smaller $\Gamma_{\text{eff}}$ values (e.g., 0.8) for these four quasars would not affect significantly our results. The X-ray properties for sample A are listed in Table 2.

4. Results

4.1. $\alpha_{\text{OX}}$–$L_{2500\AA}$ Relation

The X-ray-to-optical power-law slope parameter $\alpha_{\text{OX}}$ or its upper limit was measured for each of our sample objects. For each of the 1344 X-ray-detected objects, we derived its rest-frame 2 keV flux density ($f_{\text{2keV}}$) by normalizing the broadband counts in the simulated spectrum with the derived $\Gamma_{\text{eff}}$ value (see Section 3) to the observed broadband net counts. If a sample object is undetected in the broad band but detected in the soft (or hard) band, we normalized the soft-band (or hardband) counts in the simulated spectrum to the observed net counts. For each of the 481 X-ray-undetected objects, a 3$\sigma$ confidence level upper limit on $f_{\text{2keV}}$ was computed by normalizing the broadband counts in the simulated spectrum to the upper limit on the observed broadband counts (Section 3). The 3$\sigma$ upper limit is appropriate for the following survival analysis. The $f_{\text{2keV}}$ and $\alpha_{\text{OX}}$ parameters are listed in Table 3.

Previous studies have revealed a strong anticorrelation between $\alpha_{\text{OX}}$ and the 2500 Å monochromatic luminosity over five orders of magnitude in $L_{2500\AA}$ (e.g., Wilkes et al. 1994; Strateva et al. 2005; Steffen et al. 2006; Just et al. 2007). Figure 3 shows the $\alpha_{\text{OX}}$ versus $L_{2500\AA}$ distribution for our sample A quasars. The generalized Kendall’s $\tau$ test in the Astronomy Survival Analysis package (ASURV Rev 1.2; Isobe & Feigelson 1990; LaValley et al. 1992) confirmed a highly significant (20.4$\sigma$) anticorrelation between $\alpha_{\text{OX}}$ and $L_{2500\AA}$.

Before quantifying the $\alpha_{\text{OX}}$–$L_{2500\AA}$ relation, we attempted to exclude potentially X-ray-absorbed objects. We selected potentially X-ray-absorbed objects based on the effective power-law photon index $\Gamma_{\text{eff}}$. The mean value of $\Gamma_{\text{eff}}$ for RQ type 1 quasars has been found to be $\Gamma \approx 1.9$ (e.g., Reeves et al. 1997; Just et al. 2007). The $\Gamma_{\text{eff}}$ value generally becomes smaller if a quasar is X-ray absorbed. For the 1285 quasars in our sample that are detected in at least one of the soft and hard bands, the distribution of $\Gamma_{\text{eff}}$ is shown Figure 4(a). The $\Gamma_{\text{eff}}$ values range from $-1.4$ to $4.0$ with an average value of 1.8 and a standard deviation of 0.7, consistent with those derived in previous studies (e.g., Just et al. 2007).

We fitted the $\Gamma_{\text{eff}}$ distribution with a Gaussian function using the IDL MPFIT (Markwardt 2009) routine. The black curve in Figure 4(a) is the best-fit Gaussian profile, which has a mean of 1.78 and a standard deviation of 0.52. We note that there are 553 objects among these 1285 quasars that are detected in only one of the soft and hard bands, and their $\Gamma_{\text{eff}}$ values are best-guess estimates (Section 3). The $\Gamma_{\text{eff}}$ values that deviate from the mean by more than 2.5$\sigma$ (i.e., $\Gamma_{\text{eff}} \lesssim 0.5$ or $\Gamma_{\text{eff}} \gtrsim 3.1$) come predominantly from these 553 objects. Excluding these 553 objects, the distribution of $\Gamma_{\text{eff}}$ for the 732 objects that are detected in both the soft and hard bands is shown in Figure 4(b). The best-fit Gaussian profile has a mean of 1.70 and a standard deviation of 0.45.

Based on the above $\Gamma_{\text{eff}}$ distributions, we adopted $\Gamma_{\text{eff}} = 1.26$ to be the threshold separating X-ray-unabsorbed and potentially X-ray-absorbed quasars in this paper (i.e., an object with $\Gamma_{\text{eff}} < 1.26$ is considered an absorbed quasar), which corresponds to a negative 1$\sigma$ deviation from the means of the Gaussian distributions. We have verified that adopting a larger $\Gamma_{\text{eff}}$ value of 1.4 as the threshold would not significantly affect our results below. We thus excluded 230 quasars with $\Gamma < 1.26$ in our sample when fitting the $\alpha_{\text{OX}}$–$L_{2500\AA}$ relation.

We utilized the EM (estimate and maximize) algorithm in ASURV to derive the linear regression parameters. The best-fit relation for the remaining 1595 quasars is

$$\alpha_{\text{OX}} = (-0.224 \pm 0.008)\log(L_{2500\AA}) + (5.373 \pm 0.254),$$

which is shown as the solid black line in Figure 3. The Just et al. (2007) $\alpha_{\text{OX}}$–$L_{2500\AA}$ relation is shown for comparison.

The slope of the best-fit $\alpha_{\text{OX}}$–$L_{2500\AA}$ relation is steeper than that from Just et al. (2007). We note that our sample A spans about three orders of magnitude in $L_{2500\AA}$ [29.3 $\leq \log(L_{2500\AA}) \leq 32.0$], while the Just et al. (2007) sample spans a much larger $L_{2500\AA}$ range and extends to lower luminosities [27.5 $\leq \log(L_{2500\AA}) \leq 32.5$]. Therefore, the apparent difference between the $\alpha_{\text{OX}}$–$L_{2500\AA}$ slope of this study and that of Just et al. (2007) may result from the different UV luminosity ranges. The difference is consistent with the Steffen et al. (2006) interpretation that the $\alpha_{\text{OX}}$–$L_{2500\AA}$ slope becomes steeper at higher UV luminosities. We also note that our $\alpha_{\text{OX}}$–$L_{2500\AA}$ relation is consistent with that derived in a recent study by Timlin et al. (2020).

4.2. X-Ray-weak Quasars and Their Fraction

We calculated the $\Delta\alpha_{\text{OX}}$ parameter, defined as the difference between the measured $\alpha_{\text{OX}}$ and that expected from the best-fit $\alpha_{\text{OX}}$–$L_{2500\AA}$ relation (Equation 3), $\Delta\alpha_{\text{OX}} = \alpha_{\text{OX}} - \alpha_{\text{OX}}(L_{2500\AA})$. In order to define the X-ray-weak population, we examined the distribution of $\Delta\alpha_{\text{OX}}$.
values, which is shown in Figure 5. Of the 1825 objects in our sample, 65 (including one X-ray-undetected object) have \( \Delta \alpha_{O\!x} \leq -0.3 \) but only 11 have \( \Delta \alpha_{O\!x} \geq 0.3 \), which causes the apparent asymmetry of the \( \Delta \alpha_{O\!x} \) distribution. The distribution of the X-ray-detected objects can be well described by a Gaussian profile plus a negative tail with \( \Delta \alpha_{O\!x} < -0.3 \), indicating the existence of a small population of X-ray-weak quasars. Based on the \( \Delta \alpha_{O\!x} \) distribution, we adopted \( \Delta \alpha_{O\!x} = -0.3 \) as the threshold separating X-ray-normal and X-ray-weak quasars in this paper (i.e., an object with \( \Delta \alpha_{O\!x} \leq -0.3 \) is considered an X-ray-weak quasar). We note that the \( \Delta \alpha_{O\!x} \) distribution for the 1114 \( \Gamma \geq 1.26 \) X-ray-detected objects (Section 4.1) has a standard deviation of 0.12. Thus, \( \Delta \alpha_{O\!x} = -0.3 \) corresponds to a negative 2.5\( \sigma \) deviation from the zero point.

Gibson et al. (2008a) have measured upper limits on the fractions of quasars that are X-ray weak by given factors. In this study, as the number of X-ray quasars has been increased significantly, we can better constrain the X-ray-weak fractions. Considering that the X-ray-undetected quasars have only upper limit constraints on their X-ray-weakness factors, we utilized the Kaplan–Meier estimator provided in the ASURV package, which works with censored data, to derive the best estimates and uncertainties for these fractions. Figure 6 shows the fraction of quasars with \( f_{\text{weak}} \geq x \) versus \( x \). The X-ray-weakness factor \( f_{\text{weak}} \) was measured from \( \Delta \alpha_{O\!x} \) as \( f_{\text{weak}} = 10^{-\Delta \alpha_{O\!x}/0.3838} \), and the X-ray-weak threshold \( \Delta \alpha_{O\!x} \leq -0.3 \) corresponds to an X-ray-weakness factor of \( f_{\text{weak}} \geq 6.0 \). We found the fraction of X-ray-weak quasars to be \( 5.8\% \pm 0.7\% \); the 1\( \sigma \) uncertainties were calculated following the method of Avni et al. (1980). Additionally, the fractions of quasars that are X-ray weak by factors of \( f_{\text{weak}} \geq 10 \) (\( \Delta \alpha_{O\!x} \leq -0.38 \)), \( f_{\text{weak}} \geq 20 \) (\( \Delta \alpha_{O\!x} \leq -0.50 \)), and \( f_{\text{weak}} \geq 50 \) (\( \Delta \alpha_{O\!x} \leq -0.65 \)) are \( 2.7\% \pm 0.5\% \), \( 1.3\% \pm 0.3\% \), and \( 0.74\% \pm 0.26\% \), respectively.

4.3. Fractions of X-Ray-weak Quasars among Two Subsamples

We note that the Kaplan–Meier estimator used in Section 4.2 assumes that the intrinsic distribution of the censored data is the same as that of the measured data (Feigelson & Nelson 1985). The assumption is sensible if the X-ray nondetections are simply caused by shallower Chandra coverage, but it is not valid if many of the X-ray-undetected quasars are indeed more X-ray weak (having a more negative \( \Delta \alpha_{O\!x} \) distribution) than the X-ray-detected quasars. Given Figure 2, it appears that the X-ray-undetected quasars in general have shallower Chandra coverage than the X-ray-detected quasars, but it is not sufficient to justify the assumption above, especially when we are interested in the exceptionally X-ray-weak quasars. Therefore, in this subsection, we constructed, without direct reference to X-ray source properties, two subsamples of quasars out of sample A that do not have censored \( \Delta \alpha_{O\!x} \) values (all X-ray detected), and then we compared the fractions of X-ray-weak quasars among these subsamples to those in sample A.
The principle for selecting quasars that are likely X-ray detected is to limit the sample to bright quasars and to also limit the X-ray observations to those with good sensitivity (relatively large exposures and small off-axis angles; e.g., Figure 2). Because the DR7 and DR10 quasar catalogs have significantly different depths, we cannot select bright quasars from these two catalogs using a uniform brightness criterion. Thus, we constructed a subsample of quasars from the DR7 and DR10 catalogs, respectively. The detailed criteria are as follows:

1. \( i \)-band magnitude \( m_i < 19.6 \) (\( m_i < 21.1 \)) for DR7 (DR10) quasars,
2. effective exposure time \( >2.5 \text{ ks} \) (\( >6.3 \text{ ks} \)) and off-axis angle \( <9^{\circ}/8 <8^{\circ}/2 \) for DR7 (DR10) quasars. We adopted more stringent exposure-time and off-axis angle criteria for DR10 quasars, as they are on average optically fainter than DR7 quasars.

These two criteria resulted in a subsample of 218 (208) quasars in DR7 (DR10), and we refer to this subsample as sample B (sample C). The selections of samples B and C are also listed in Table 1. Quasars in sample B or sample C are all X-ray detected, and thus we can compute the fraction of X-ray-weak quasars among each subsample directly without employing the Kaplan–Meier estimator. We stress that we do not require X-ray detections in the construction of samples B and C, which are simply the outcomes of the appropriate brightness and X-ray sensitivity criteria listed above.

Given our X-ray-weak definition of \( \Delta \alpha_{\text{ox}} \leq -0.3 \), sample B contains 12 X-ray-weak quasars, corresponding to an X-ray-weak fraction of \( 5.5^{\pm 2.0}_{-1.2} \% \) (12/218); the 1σ binominal confidence intervals were calculated following the method of Cameron (2011). Figure 7(a) shows the fraction of quasars with \( f_{\text{weak}} \geq x \) versus \( x \) in sample B. The fraction of quasars that are X-ray weak by a factor of \( f_{\text{weak}} \geq 10 \) (\( \Delta \alpha_{\text{ox}} \leq -0.38 \)) in sample B is \( 3.2^{\pm 1.7}_{-0.8} \% \) (7/218). In sample C, there are 14 X-ray-weak quasars, corresponding to an X-ray-weak fraction of \( 6.7^{\pm 2.2}_{-1.4} \% \) (14/208). Figure 7(b) shows the fraction of quasars with \( f_{\text{weak}} \geq x \) versus \( x \) in sample C. The \( f_{\text{weak}} \geq 10 \) fraction in sample C is \( 2.9^{\pm 1.7}_{-0.8} \% \) (6/208). The X-ray-weak fraction curve for sample A is also plotted in Figure 7, showing general consistency with the curve for sample B or sample C.

We note that the fractions of X-ray-weak quasars among samples B and C are consistent within the uncertainties. Samples B and C probe slightly different quasar populations in terms of their optical brightness and X-ray coverage, and the fractions of X-ray-weak quasars among them are not necessarily the same, but our current data are not sufficient to determine if the fraction has any luminosity dependence. In order to increase the sample size and reduce the fraction uncertainties, we combine samples B and C (sample B+C) in our following analysis. In this combined sample, the X-ray-weak and \( f_{\text{weak}} \geq 10 \) fractions become \( 6.1^{\pm 1.4}_{-1.0} \% \) (26/426) and \( 3.1^{\pm 1.1}_{-0.6} \% \) (13/426), respectively. Comparing these fractions to those in sample A, we found that they are consistent within the uncertainties. The Kaplan–Meier estimator appears to provide a reasonable estimate of the fraction of X-ray-weak quasars in sample A, and the difference between the quasar populations in sample A and sample B + C does not appear to affect significantly the X-ray-weak fractions.

5. Discussion

5.1. Fractions of X-Ray-weak Quasars

Our study found that a small fraction of optically selected, non-BAL, type 1 quasars do show weak X-ray emission. Based on our sample A of 1825 quasars, 1344 (74% \( \pm 1\% \)) of which are X-ray detected, the fraction of X-ray-weak (\( f_{\text{weak}} \geq 6 \)) quasars is \( 5.8\% \pm 0.7\% \) and the fraction of \( f_{\text{weak}} \geq 10 \) quasars is \( 2.7\% \pm 0.5\% \). Based on our subsample B + C of 426 quasars that are composed of X-ray detections only, the fraction of X-ray-weak quasars is \( 6.1^{\pm 1.4}_{-1.0} \% \) and the fraction of \( f_{\text{weak}} \geq 10 \) quasars is \( 3.1^{\pm 1.1}_{-0.6} \% \). These small but nonnegligible fractions of X-ray-weak quasars challenge the ubiquity of quasar X-ray emission, and they also require additional physical mechanisms internal or external to the corona that can suppress the observed X-ray emission; we discuss some possible causes for the X-ray-weak quasars in Section 5.2 below.

Our current investigation was motivated by the Gibson et al. (2008a) study that used a much smaller sample of quasars. Based on sample B of Gibson et al. (2008a), which is similar to our sample B + C here composed of only X-ray detections but only has 139 quasars, the fraction of \( f_{\text{weak}} \geq 10 \) quasars is considered to be \( \leq 2\% \). Their result is consistent with ours here considering the uncertainties of both studies.

Recently, a few studies have found much larger fractions of X-ray-weak quasars, albeit among samples with very limited sizes. For example, Nardini et al. (2019) found seven X-ray-weak quasars among 29 very luminous RQ quasars at \( z \approx 3.0–3.3 \), corresponding to an X-ray-weak fraction of 24%. In addition, Zappacosta et al. (2020) found 4–5 X-ray-weak quasars among 13 hyperluminous RQ quasars at \( z \approx 2–4 \), corresponding to an X-ray-weak fraction of \( \approx 30\%–40\% \). The definitions of X-ray-weak quasars in these studies are slightly different from our adopted \( \Delta \alpha_{\text{ox}} \leq -0.3 \) here, but adopting their definitions would not significantly change the fractions of X-ray-weak quasars in our samples and they are still only about 5%–7%. There are several factors that may contribute to the discrepancy between the fractions of X-ray-weak quasars, and a detailed comparison between their result and the Gibson et al. (2008a) sample B result was also
presented in Section 5.7 of Nardini et al. (2019). We list two factors below that may be responsible for most of the discrepancy.

1. The fractions among small quasar samples are vulnerable to contamination from a few X-ray-weak BAL quasars. There may be X-ray-weak BAL quasars missed in the Nardini et al. (2019) and Zappacosta et al. (2020) samples (e.g., Section 5.8 and Appendix B of Nardini et al. 2019), and even one such quasar in the sample would bias the fraction significantly.

2. The fraction of X-ray-weak quasars likely has a luminosity dependence, and it becomes larger among more-luminous quasars. The main difference between the Nardini et al. (2019) and Zappacosta et al. (2020) samples and our sample is the quasar luminosity. The 29 quasars in Nardini et al. (2019) and the 13 quasars in Zappacosta et al. (2020) have a UV luminosity range of $31.8 \leq \log(L_{2500\AA}) \leq 32.5$ except for one object, while our sample quasars have $29.3 \leq \log(L_{2500\AA}) \leq 32.0$. We do not have a sizable number of very luminous quasars for direct comparison, but if we limit our sample to the 30 most-luminous quasars in sample A, which have $31.4 \leq \log(L_{2500\AA}) \leq 32.0$ and a median $\log(L_{2500\AA})$ value of 31.5, the fraction of X-ray-weak quasars in this high-luminosity sample becomes $16\% \pm 8\%$, much larger compared to the fraction in the full sample. If we limit our sample to the 50 most-luminous quasars in sample A, which have $31.3 \leq \log(L_{2500\AA}) \leq 32.0$ and a median $\log(L_{2500\AA})$ value of 31.4, the X-ray-weak fraction becomes $15\% \pm 6\%$. Such a luminosity dependence for the fraction of X-ray-weak quasars is in general agreement with our interpretations of X-ray-weak quasars as WLQs (e.g., Luo et al. 2015; Ni et al. 2018; Section 5.2.1) or due to extreme X-ray variability (e.g., Liu et al. 2019; Ni et al. 2020; Section 5.2.3), where quasars accreting at high Eddington ratios may have X-ray absorption from a geometrically thick inner accretion disk or its associated outflow; the fraction of such quasars is likely higher among more-luminous samples. The relevance of the enhanced fraction of X-ray-weak quasars to WLQs is also noted in both Nardini et al. (2019) and Zappacosta et al. (2020). We also note that if we divide our sample A into a high-luminosity subsample and a low-luminosity subsample at the median luminosity of $\log(L_{2500\AA}) = 30.45$, the fractions of X-ray-weak quasars among the two subsamples are $6.2\% \pm 1.0\%$ and $5.4\% \pm 1.0\%$, respectively. Such a small difference indicates that the enhanced fraction of X-ray-weak quasars (probably related to the enhanced fraction of WLQs) is mostly evident among very luminous quasars.

Given the above comparisons, we stress that the fractions of X-ray-weak quasars derived in this study are mostly applicable to quasar samples sharing similar properties to our SDSS quasars here (Table 1), and extra caution is needed if quoting the fractions for quasars with substantially different luminosities.

Finally, we constrain the fraction of intrinsically X-ray-weak quasars. In sample B + C, there are nine X-ray objects with $\Gamma_{\text{eff}} \geq 1.26$ (including three with $\Gamma_{\text{eff}}$ set to 1.8), which we consider to be candidates for intrinsically X-ray-weak quasars. Thus, the fraction of intrinsically X-ray-weak quasars within the non-BAL quasar population is $1.4^{+0.8\%}_{-0.4\%} - 2.1^{+0.9\%}_{-0.8\%}$ ($6/426–9/426$). This fraction would be $1.2^{+0.3\%}_{-0.3\%} - 1.9^{+0.5\%}_{-0.5\%}$ ($5/426–8/426$) if we consider X-ray objects with $\Gamma_{\text{eff}} \geq 1.4$ to be candidates for intrinsically X-ray-weak quasars. Based on the X-ray properties of 35 Large Bright Quasar Survey BAL quasars, Liu et al. (2018) estimated the fraction of intrinsically X-ray-weak quasars within the BAL quasar population to be $5.7^{+3.7\%}_{-1.9\%} - 23^{+6\%}_{-5\%}$ ($2/35–8/35$), which is significantly higher than the fraction within the non-BAL quasar population derived here. These results indicate that intrinsically X-ray-weak quasars may be preferentially found in BAL quasars (e.g., Luo et al. 2014; Liu et al. 2018), and intrinsically X-ray-weak non-BAL quasars like PHL 1811 are extremely rare.
We consider an X-ray-weak quasar to be in the unclassified category. We adopted \( \Delta \alpha_{\text{OX}} = -0.3 \) to be the threshold separating X-ray-normal and X-ray-weak quasars (Section 4.2). All undetected X-ray-weak quasars in sample A have fixed X-ray photon indices of \( \Gamma_{\text{eff}} = 1.8 \); the numbers of detected X-ray-weak quasars with fixed \( \Gamma_{\text{eff}} \) values of 1.8 (see Section 3) are listed in the “Unclear” columns.

\( ^a \) We adopted C IV \( \text{REW} = 16 \, \text{Å} \) to be the threshold separating WLQs and normal quasars (Section 5.2.1).

\( ^b \) We adopted \( \Delta(g - i) = 0.2 \) to be the threshold separating red and normal quasars (Section 5.2.2).

\( ^c \) We consider an X-ray-weak quasar to be in the unclassified population if it is neither a WLQ nor a red quasar (Section 5.2.3).

### 5.2. Nature of X-Ray-weak Quasars

We discuss the possible nature of the X-ray-weak quasars found in this study. We focus on the 26 X-ray-weak quasars \((\Delta \alpha_{\text{OX}} \leq -0.3)\) quasars in sample B + C (12 in sample B and 14 in sample C). We also present the overall properties for the X-ray-weak quasars in sample A. We consider that there are three types of X-ray-weak quasars based on the optical spectral features: WLQs, red quasars, and unclassified X-ray-weak quasars. A breakdown of the X-ray-weak quasars in samples A and B + C is listed in Table 5.

### 5.2.1. X-Ray-weak WLQs

With a large fraction \( (\geq 50\%) \) of quasars showing weak X-ray emission, WLQs represent one population of X-ray-weak quasars (e.g., Wu et al. 2012; Luo et al. 2015; Ni et al. 2018; Timlin et al. 2020). X-ray-weak WLQs were also found to have on average a small effective photon index, suggestive of X-ray absorption (e.g., Luo et al. 2015). Their X-ray emission may be absorbed by “shielding gas” (e.g., Wu et al. 2011, 2012) or a geometrically thick inner accretion disk (e.g., Luo et al. 2015; Ni et al. 2018, 2020).

There is no uniform definition for WLQs. For high-redshift \((z > 2.200)\) quasars, WLQs are generally selected using the REW of the Ly\( \alpha + N \) line emission lines. Shemmer et al. (2009) defined WLQs to be quasars with \( \text{Ly}\alpha + N \) \text{REW} \( < 10 \, \text{Å} \). Diamond-Stanic et al. (2009) defined WLQs to be those with \( \text{Ly}\alpha + N \) \text{REW} \( < 15.4 \, \text{Å} \) (\( > 3\sigma \) deviation from the mean of the log-normal distribution). For low-redshift \((z \leq 2.200)\) quasars, which do not have \( \text{Ly}\alpha + N \) coverage in their optical spectra, the definition of WLQs is commonly based on other strong emission lines (e.g., C IV, C III, Mg II, and H\( \beta \)). Wu et al. (2012) and Luo et al. (2015) selected WLQs from the Plotkin et al. (2010b) catalog, which has \text{REW} \( \leq 5 \, \text{Å} \) for all emission features. Recently, Ni et al. (2018) called quasars with C IV \text{REW} \( < 7.0 \, \text{Å} \) “extreme” WLQs and quasars with C IV \text{REW} \( = 7.0 - 15.5 \, \text{Å} \) “bridge” WLQs, which have emission-line features in between those of extreme WLQs and typical quasars.

The C IV \text{REW} values of our 26 X-ray-weak quasars in sample B + C range from 6.6 to 56.8 \, \text{Å}, with a median value of 24.4 \, \text{Å} and a mean value of 25.6 \, \text{Å}. We adopted C IV \text{REW} \( = 16 \, \text{Å} \) to be the threshold separating WLQs and normal quasars in this paper. Our more inclusive definition C IV \text{REW} \( < 16 \, \text{Å} \) for WLQs corresponds to a \( > 2\sigma \) deviation from the mean of the log-normal distribution for SDSS quasars, where the distribution of C IV \text{REW} shows an apparent tail toward small values (see Section 3.2 of Wu et al. 2012). Because all of our sample objects have C IV coverage, we consider this criterion appropriate for this study. For any sample object that has both SDSS DR7 and BOSS DR10 spectra, we consider it a WLQ if either spectrum has C IV \text{REW} \( < 16 \, \text{Å} \). Given this criterion, sample B + C contains seven X-ray-weak WLQs. Figure 8 shows the spectra of these seven quasars. We note that three of them (J1219+1244, J1350+2618, and J1457+2218) have both SDSS DR7 and BOSS DR10 spectra. For J1219+1244 and J1350+2618, all of their spectra satisfy the WLQ criterion, while for J1457+2218, only its BOSS DR10 spectrum does.

Given our WLQ definition of C IV \text{REW} \( < 16 \, \text{Å} \), sample B + C contains 20 WLQs, seven of which are X-ray weak, corresponding to an X-ray-weak fraction of \( 35\% \). The seven X-ray-weak WLQs have a C IV \text{REW} distribution comparable to the other 13 X-ray-normal WLQs; e.g., the median C IV \text{REW}s are 11.9 and 9.2 \, \text{Å}, respectively. By contrast, the fraction of X-ray-weak quasars is only \( 4.7^{+1.3}_{-0.8}\% \) (19/406) among the non-WLQs in sample B + C. Thus, WLQs show significantly higher X-ray-weak fraction when compared to non-WLQs. These results confirm previous findings that WLQs represent one population of X-ray-weak quasars (e.g., Wu et al. 2012; Luo et al. 2015; Ni et al. 2018).

Ni et al. (2018) investigated a sample of 32 WLQs selected mainly from the Shen et al. (2011) and Plotkin et al. (2010b) catalogs. They adopted a definition of C IV \text{REW} \( < 15.5 \, \text{Å} \) for “extreme”-“bridge” WLQs, which is similar to our WLQ definition, and the fraction of X-ray-weak objects within their WLQ sample is \( 44^{+8}_{-5}\% \) (14/32). We note that Ni et al. (2018) adopted \( \Delta \alpha_{\text{OX}} < -0.2 \) to define X-ray-weak quasars. If we use this same definition, sample B + C would contain 10 X-ray-weak WLQs, and the X-ray-weak fraction for WLQs would be \( 50\% \pm 11\% \), which is in agreement with Ni et al. (2018).

Wu et al. (2011) proposed a “shielding-gas” scenario to unify X-ray-normal and X-ray-weak WLQs. In this scenario, a small fraction of the quasar population has high-ionization shielding gas lying between the SMBH and the broad emission-...
line region (BELR). With high column density and large BELR covering factor, the shielding gas is able to prevent most, if not all, X-ray emission and other ionizing continuum from reaching the BELR. If such a quasar is viewed through the shielding gas, an X-ray-weak WLQ is seen; if it is viewed from other orientations, an X-ray-normal WLQ is seen. The average hard X-ray spectrum via stacking analyses, which is suggestive of X-ray absorption, further supports the shielding-gas scenario (Luo et al. 2015).

The $\Gamma_{\text{eff}}$ values of the seven X-ray-weak WLQs in sample $B + C$ are listed in Table 6. Given our $\Gamma_{\text{eff}} < 1.26$ criterion for being potentially X-ray absorbed (Section 4.1), four of the seven X-ray-weak WLQs are potentially X-ray absorbed, with their $\Gamma_{\text{eff}}$ values ranging from $-0.8$ to $1.1$. The small effective photon indices for these four X-ray-absorbed WLQs are consistent with the shielding-gas scenario (e.g., Wu et al. 2011, 2012). In addition, there are two apparently unabsorbed X-ray-weak WLQs, J1350+2618 and J1457+2218, which have $\Gamma_{\text{eff}} = 2.0^{+1.1}_{-1.0}$ and $1.6^{+0.3}_{-0.2}$, respectively. These two are good candidates for intrinsically X-ray-weak quasars. One of them, J1457+2218, is detected in all three X-ray bands. With 70 photons in the broad band, it is the only object that has $>50$ broadband photons in sample $B + C$. We present the X-ray spectral analysis of J1457+2218 in the Appendix. Another quasar, J1219+1244, is undetected in both the soft and hard bands and has a fixed photon index of $\Gamma_{\text{eff}} = 1.8$, and thus it is unclear whether this object is X-ray absorbed.

However, we note that, except for J1457+2218, the other six X-ray-weak WLQs have only 2–22 photons in the broad band, leading to substantial uncertainties of the effective photon indices $\Gamma_{\text{eff}}$ (see Table 6). We also note that four X-ray-weak WLQs (J0039+0051, J1219+1244, J1347+2609, and J1350+2618) are mini-BAL quasars (see Section 5.2.3 below), and their X-ray weakness might also be related to their mini-BAL features, although mini BALs do not necessarily lead to weak X-ray emission.

Based on the Wu et al. (2011) shielding-gas scenario, Luo et al. (2015) proposed that the shielding gas may be a geometrically thick inner accretion disk. When a quasar is accreting at a high Eddington ratio ($L_{\text{bol}}/L_{\text{Edd}} \gtrsim 0.3$), its inner
accretion disk may become significantly puffed up (e.g., Koratkar & Blaes 1999; Blaes et al. 2001; Laor & Davis 2011; Slone & Netzer 2012; Netzer & Trakhtenbrot 2014). The puffed-up disk can block nuclear X-rays and other ionizing photons from reaching an equatorial BELR. Thus, an X-ray-weak WLQ can be seen when such a quasar is viewed through the thick inner disk.

To test the Luo et al. (2015) model, we estimated the $L_{\text{bol}}/L_{\text{Edd}}$ values of our sample objects from their bolometric luminosities and SMBH masses. We measured SMBH masses using the Mg II (Vestergaard & Osmer 2009) or C IV (Vestergaard & Peterson 2006) virial estimator. We preferred Mg II-based estimates to C IV-based estimates when calculating the SMBH masses, because the C IV virial estimator is more uncertain. We calculated the bolometric luminosities as $L_{\text{bol}} = 5.15 \times L_\lambda (3000 \, \text{Å})$ for Mg II-based estimates or $L_{\text{bol}} = 3.81 \times L_\lambda (1350 \, \text{Å})$ for C IV-based estimates (Shen et al. 2011). Of the seven X-ray-weak WLQs in sample B + C, all but one (J1350+2618) have Mg II-based virial SMBH masses.

The $L_{\text{bol}}/L_{\text{Edd}}$ values of our seven X-ray-weak WLQs in sample B + C range from 0.06 to 0.79, with a median value of 0.16. A Kolmogorov–Smirnov test indicates no significant difference between the $L_{\text{bol}}/L_{\text{Edd}}$ values for the seven X-ray-weak WLQs and the 406 non-WLQs in sample B + C ($p = 0.44$), which does not support the high-$L_{\text{bol}}/L_{\text{Edd}}$ scenario for WLQs. However, we note that the Mg II- or C IV-based virial masses are less reliable compared to H β-based virial masses, and the systematic uncertainties associated with the virial estimates might be as large as $\geq$0.4 dex (e.g., Shen et al. 2011). Furthermore, virial estimates are most likely to fail at high Eddington ratios (e.g., Marconi et al. 2008, 2009; Netzer & Marziani 2010). Thus, the $L_{\text{bol}}/L_{\text{Edd}}$ values derived from Mg II- or C IV-based estimates may be highly uncertain. Near-infrared spectroscopy covering the H β line is needed to provide more accurate $L_{\text{bol}}/L_{\text{Edd}}$ estimates.

In sample A, there are 60 WLQs, 35 of which are X-ray detected and 25 of which are X-ray undetected. Utilizing the Kaplan–Meier estimator in ASURV, we found the X-ray-weak fraction within the 60 WLQs to be $35\% \pm 8\%$, which is consistent with that derived from sample B + C. Of the nine detected X-ray-weak WLQs in sample A, six are likely X-ray absorbed with $\Gamma_{\text{eff}}$ values ranging from $-0.8$ to $1.1$, and two (both included in sample B+C) are potentially X-ray unabsorbed. The other WLQ (included in sample B+C) is undetected in both the soft and hard bands, and thus it is unclear if it is X-ray absorbed.

5.2.2. X-Ray-weak Red Quasars

In addition to WLQs, there exists a population of red type 1 quasars that can be X-ray weak (e.g., Wilkes et al. 2005; Hall et al. 2006). Previous X-ray studies have demonstrated that quasars with the reddest optical colors at their redshifts are more likely to be X-ray absorbed than typical quasars (e.g., Wilkes et al. 2005), although some of the reddest quasars may show no evidence of X-ray absorption or X-ray weakness (e.g., Hall et al. 2006). These optically red quasars may be X-ray obscured by dusty gas, which also extincts the UV continuum, perhaps from a starburst disk surrounding their accreting SMBHs (e.g., Hickox & Alexander 2018).

Broadband photometric studies of SDSS quasars have revealed a strong dependence of quasar optical/UV colors upon redshift (e.g., Richards et al. 2001), and the relative $g-i$ color, $\Delta(g-i)$, is a useful redshift-independent indicator of the optical/UV spectral shape (e.g., Richards et al. 2003). For a quasar at a given redshift, $\Delta(g-i)$ is defined as the difference between the $g-i$ color of that quasar and the modal $g-i$ value of quasars at that redshift. $\Delta(g-i) > 0$ indicates a redder-than-average continuum, while $\Delta(g-i) < 0$ indicates a bluer-than-average continuum. The $\Delta(g-i)$ distribution for SDSS quasars is roughly Gaussian but has a distinct red tail with $\Delta(g-i) > 0.2$, which is indicative of dust reddening (Richards et al. 2003). Based on the $\Delta(g-i)$ distribution, Hall et al. (2006) adopted $\Delta(g-i) > 0.2$ to select red quasars for X-ray study.

The $\Delta(g-i)$ values of the 26 X-ray-weak quasars in our sample B + C range from $-0.20$ to 0.82, with a median value of 0.11 and a mean value of 0.17. Following Hall et al. (2006), we adopted $\Delta(g-i) = 0.2$ to be the threshold separating red and normal quasars in this paper. Given this criterion, sample B + C contains eight X-ray-weak red quasars, with $\Delta(g-i)$ values ranging from 0.29 to 0.82. We note that although the $\Delta(g-i) > 0.2$ criterion was designed to select dust-reddened quasars, the possibility of selecting unreddened quasars (with intrinsically red continua) cannot be entirely excluded. However, given that all our X-ray-weak red quasars in sample B + C have $\Delta(g-i) > 0.3$, they are likely to be dominated by dust-reddened quasars (e.g., Richards et al. 2003; Hall et al. 2006; Krawczyk et al. 2015).

Given our red quasar definition of $\Delta(g-i) > 0.2$, sample B + C contains 63 red quasars, eight of which are X-ray weak, corresponding to an X-ray-weak fraction of 13.5%. By contrast, only $5.0^{+1.8}_{-0.8}$% (18/363) of non-red quasars are X-ray weak. If we exclude red WLQs, the X-ray-weak fraction for red and non-red quasars within sample B + C are $9.3^{+5.2}_{-2.6}$% (5/54) and $4.0^{+1.2}_{-0.6}$% (14/352), respectively. These results suggest that red quasars are likely to be another population of X-ray-weak quasars in addition to WLQs, although red quasars apparently have a smaller X-ray-weak fraction than WLQs.

Of the eight X-ray-weak red quasars, three (J0039+0051, J1219+1244 and J1338+J2922) are red WLQs with C IV REW < 12 Å. J0039+0051 and J1338+J2922 are likely X-ray absorbed with $\Gamma_{\text{eff}} = -0.8^{+1.4}_{-1.1}$ and $1.1^{+1.4}_{-1.0}$, respectively. Interestingly, J0039+0051 is the reddest ($\Delta(g-i) = 0.82$) X-ray-weak quasar in sample B + C, while J1338+J2922 has the highest Eddington ratio ($L_{\text{bol}}/L_{\text{Edd}} = 0.79$; see Section 5.2.1) among X-ray-weak WLQs in sample B + C. The other object, J1219+1244, has a fixed photon index of $\Gamma_{\text{eff}} = 1.8$ (see Section 5.2.1).

Of the remaining five X-ray-weak red quasars, four are likely X-ray absorbed, as their $\Gamma_{\text{eff}}$ values range from $-1.2$ to 1.1. The other quasar, J1522+0836, is undetected in both the soft and hard bands and has a fixed photon index of $\Gamma_{\text{eff}} = 1.8$. Because dust causes optical/UV reddening and gas causes X-ray absorption, the reddened optical/UV color together with absorbed X-ray emission indicates that these X-ray-weak red quasars may have optical/UV and X-ray absorption from dusty gas (Hall et al. 2006), perhaps from a starburst disk (e.g., Thompson et al. 2005; Ballantyne 2008).

We note that J1002+0203, the second reddest ($\Delta(g-i) = 0.74$) X-ray-weak quasar in sample B + C, shows relatively weak C IV emission with REW = 19 Å (although not satisfying our WLQ criterion). It has 27 broadband counts and is detected in all three X-ray bands. J1002+0203 has a small photon index of $\Gamma_{\text{eff}} = 1.1$ and a high Eddington ratio of 2.4.
\( L_{\text{Bal}} / L_{\text{Edd}} = 0.59 \). Thus, the X-ray weakness of this quasar might also be explained via the thick inner-disk scenario for WLQs (e.g., Luo et al. 2015; Ni et al. 2018).

Although their small \( \Gamma_{\text{eff}} \) values suggest X-ray absorption, these X-ray-weak red quasars only have 2–27 photon counts in the broad band, and thus, the uncertainties on the effective photon indices \( \Gamma_{\text{eff}} \) are large. In addition, there are five X-ray-weak red quasars (J0039+0051, J0228+0040, J1219+1244, J1239+1221, and J1522+0836) that are mini-BAL quasars (see Section 5.2.3 below), and their X-ray weakness might be related to their mini-BAL features, although mini-BALs do not necessarily cause weak X-ray emission.

In sample A, there are 193 red quasars, 147 of which are X-ray detected and 46 of which are X-ray undetected. Utilizing the Kaplan–Meier estimator in ASURV, we found the photon fraction within the 193 red quasars to be 12% ± 3%, which is consistent with that derived from sample B + C. Of the 10 detected X-ray-weak, red, non-WLQs in sample A, eight are likely X-ray absorbed and their \( \Gamma_{\text{eff}} \) values range from −1.2 to 1.1. Another one (J1237+6203; not included in sample B + C) is potentially X-ray unabsorbed with \( \Gamma_{\text{eff}} = 1.6 \pm 0.4 \). Its large \( \Gamma_{\text{eff}} \) value suggests that this red non-WLQ is a candidate for an intrinsically X-ray-weak quasar. The other one (J1522+0836; included in sample B + C) is undetected in both the soft and hard bands, and thus it is unclear whether this object is X-ray absorbed.

### 5.2.3. Unclassified X-Ray-weak Quasars

In addition to the 7 WLQs and 5 red non-WLQs, there are another 14 objects in sample B + C that are X-ray weak. They do not have substantially unusual spectral features like WLQs or red quasars, and the reasons for their X-ray weakness remain unclear. We consider an X-ray-weak quasar that is neither a WLQ nor a red quasar to be in the unclassified category (see Table 5). Figure 9 shows the SDSS spectra of the 14 unclassified X-ray-weak quasars in sample B + C. We proceed by enumerating some possible explanations for their weak X-ray emission.

1. One possible explanation for their X-ray weakness is relatively weak C IV line emission. There are five X-ray-weak objects (J0050−0054, J0157−0056, J0941+3946, J1235+2805, and J1629+2319) in the unclassified category that have C IV REW ranging from 16 to 25 Å. Their relatively weak emission lines (although not satisfying our WLQ definition of C IV REW < 16 Å) may explain their X-ray weakness following Section 5.2.1. However, we note that a relatively weak C IV emission line does not necessarily lead to weak X-ray emission. For example, of the 46 quasars with C IV REW between 16 and 25 Å in Sample B + C, 37 (80%–93%) are X-ray normal (see also Section 5.2 of Ni et al. 2018). Therefore, it is just one possibility that the X-ray weakness of these five objects may be related to their relatively weak C IV emission lines.

2. The second explanation is relatively red optical/UV color following Section 5.2.2. One unclassified X-ray-weak object, J1259−0132, has \( \Delta(g − i) = 0.11 \). Visual inspection of its SDSS spectrum (see Figure 9) confirmed that J1259−0132 has a slightly redder-than-average continuum, which may explain its X-ray weakness. We note that like the relatively weak C IV emission line, a relatively red continuum does not necessarily cause weak X-ray emission either. For example, of the 29 quasars with \( 0.1 < \Delta(g − i) < 0.2 \) and visually confirmed redder-than-average continua in sample B + C, 27 (93%–95%) are X-ray normal.

3. Another possible explanation is mini BALs, which are absorption features in between those of the traditional BALs (tough width ≥2000 km s\(^{-1}\)) and narrow absorption lines (NALs; trough width <500 km s\(^{-1}\)). Mini-BAL quasars have \( \Delta \alpha_{\text{OIII}} \) values intermediate between those of BAL and non-BAL quasars (e.g., Gibson et al. 2009a; Wu et al. 2010), and some of them show X-ray absorption similar to that of BAL quasars (e.g., Gallagher et al. 2002).

Because we adopted the Trump et al. (2006) AI > 0 definition (see Section 2.2), which requires a minimum trough width of 1000 km s\(^{-1}\), to identify BAL features, we defined mini BALs using the following equation:

\[
A_{\text{Imini}} = \int_{0}^{r_{\text{med}}} (1 − f(\nu))C' d\nu. \tag{4}
\]

Similar to the AI definition, in this equation \( f(\nu) \) is the continuum-normalized flux density, and the value of \( C' \) is initially set to zero; it is set to 1 whenever the \( f(\nu) \) has been continuously less than 0.9 for a trough width of 500–1000 km s\(^{-1}\). Wu et al. (2010) suggested that mini BALs with trough widths of 500–1000 km s\(^{-1}\) appear to be related to \( \Delta \alpha_{\text{OIII}} \). We consider a sample object with \( A_{\text{Imini}} > 0 \) a mini-BAL quasar. There are five unclassified X-ray-weak quasars (J1423+0420, J1432−0111, J1601+4315, J1629+2319,\(^{18}\) and J1652+3953) in sample B + C that are mini-BAL quasars, and their X-ray weakness may be explained by their mini-BAL features. However, we caution that it is just one possibility that the X-ray weakness of these five objects may be related to their mini-BAL features, as mini-BAL quasars do not appear to be an X-ray-weak population in general. For example, among the 156 mini-BAL quasars in sample B + C given our adopted definition, 144 (92%–93%) are X-ray normal.

4. The fourth possible explanation is NALs. Visual inspection of the SDSS spectra (see Figure 9) indicated that J1118+0743 appears to exhibit narrow Al III λ1857 absorption. Its X-ray weakness may be ascribed to absorption, although like mini BALs, NAL features do not necessarily lead to weak X-ray emission either (e.g., Ganguly et al. 2001).

5. The fifth explanation is X-ray variability, and we consider this the most plausible explanation for the majority of the unclassified X-ray-weak quasars. Such variable quasars may include quasars that vary strongly in the X-ray band but not in the optical/UV, “changing-look” quasars, and quasars that show BAL disappearance or emergence.

Although most type 1 quasars show X-ray variability by factors of less than 2 (e.g., Yang et al. 2016), there is a rare population of extremely X-ray-variable quasars (e.g., PG 1211+143; Bachev et al. 2009; PG 0844+349; Gallo et al. 2011; Gibson & Brandt 2012; PHL 1092; Miniutti et al. 2012; Liu et al. 2019; Timlin et al. 2020), which can vary by factors of larger than 10 in

\(^{18}\) J1629+2319 has a relatively weak C IV emission line with REW = 24 Å, which may also explain its X-ray weakness.
X-rays but show little variation in the optical/UV bands. They become remarkably X-ray weak in the low X-ray flux state, and their X-ray weakness may be due to partial-covering absorption or inner-disk reflection (e.g., Bachev et al. 2009; Gallo et al. 2011; Miniutti et al. 2012; Liu et al. 2019; Ni et al. 2020). We note that such X-ray variability is not expected to have an X-ray-strong state, consistent with observations to date.

There also exist a few “changing-look” quasars that show strong long-term flux variability in both the optical/UV and X-ray bands (e.g., LaMassa et al. 2015). If we calculate their $\alpha_{\text{OX}}$ values based on nonsimultaneous X-ray and optical/UV observations, we may consider them to be X-ray-weak quasars whenever their X-ray dim states are combined with optically bright states. Conversely, such quasars may become X-ray strong if their

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**Figure 9.** SDSS optical/UV spectra (smoothed by a 20 pixel boxcar) for the 14 X-ray-weak quasars in the unclassified category (red curves for SDSS DR7 spectra and blue curves for BOSS DR10 spectra). The gray curve in each panel shows the SDSS composite quasar spectrum (Vanden Berk et al. 2001) for comparison. SDSS Data Release number, name, and redshift for each object are listed.
X-ray-bright states are combined with optically dim states.

There is another rare population of quasars showing emerging or disappearing BALs (e.g., McGraw et al. 2017; De Cicco et al. 2018; Rogerson et al. 2018; Sameer et al. 2019). These objects may be considered X-ray-weak quasars if they are non-BAL quasars when their optical/UV data are taken, but happen to exhibit BAL features, which cause weak X-ray emission, when their X-ray data are taken. The frequency of such highly variable X-ray absorption in quasars with emerging or disappearing BALs is presently poorly constrained. There is no X-ray-strong state for this variability.

The SDSS and Chandra observation dates for the 14 sample B + C objects in the unclassified X-ray-weak category are listed in Table 7. It is clear that their SDSS optical/UV spectra and Chandra X-ray data are not simultaneous but separated by ~1–4 yr in the rest frame. Thus, their X-ray weakness is possibly due to X-ray and/or optical/UV spectral variability effects. Based on over 15,000 SDSS quasars at z > 1.680 matched between DR7 and DR9+DR10, Rogerson et al. (2018) studied the emergence and disappearance of BAL features. They estimated the fraction of non-BAL quasars turning into BAL quasars to be 0.59% ± 0.12% over timescales of 1–3 yr in the rest frame. As the time separations between the X-ray and optical/UV observations for our sample B + C objects are comparable to the timescales of BAL variability studied in Rogerson et al. (2018), we expect to see two to three sample B + C quasars exhibiting non-BAL to BAL transitions, probably included in the 14 unclassified X-ray-weak objects.

Given our definition of potentially X-ray-absorbed quasars (Γ_{eff} < 1.26), 9 of these 14 unclassified X-ray-weak quasars are likely X-ray absorbed, with their Γ_{eff} values ranging from −0.4 to 1.0. Four quasars (J1118+0743, J0429+1548, J1601+4315, and J1629+2319) are potentially X-ray unabsorbed with Γ_{eff} = 1.3 ± 0.50, 1.4^+0.7^−0.6, 2.1^+1.0^−1.3, and 2.3^+1.1^−0.9 respectively; these are candidates for intrinsically X-ray-weak quasars.

### Table 7

| SDSS Name      | SDSS Date     | Chandra Date   | Rest-frame Separation (yr) |
|----------------|--------------|----------------|---------------------------|
| J005108.44−005438.0 | 2001 Oct 17 | 2004 Sep 2     | 0.8                       |
| J015704.11−005657.5 | 2001 Oct 17 | 2014 Nov 27    | 4.4                       |
| J083116.62+321329.6 | 2002 Dec 12 | 2007 Dec 22    | 1.8                       |
| J094138.06+394630.2 | 2011 Mar 9  | 2008 Jan 16    | 1.1                       |
| J111828.31+074300.1 | 2012 Jan 3   | 2008 Jan 31    | 1.4                       |
| J123559.06+280550.5 | 2005 Dec 25 | 2001 Jan 14    | 1.8                       |
| J125923.50−013234.9 | 2000 May 30 | 2009 Feb 28    | 3.1                       |
| J142339.87+042041.1 | 2001 May 20 | 2012 Dec 15    | 3.8                       |
| J142921.75+154841.4 | 2012 Apr 18 | 2013 Dec 6     | 0.5                       |
| J143212.69−011109.7 | 2011 Feb 26 | 2000 Mar 31    | 3.2                       |
| J160145.43+315191.6 | 2012 Jun 18 | 2003 Oct 7     | 3.2                       |
| J160408.26+174004.4 | 2010 May 22 | 2004 Jul 25    | 2.1                       |
| J162922.87+231958.2 | 2004 Aug 9  | 2013 Oct 20    | 3.0                       |
| J165209.44+395348.8 | 2012 May 27 | 2014 May 19    | 0.7                       |

X-ray-weak quasars have only 2–19 photon counts in the broad band, leading to substantial uncertainties on their Γ_{eff} values.

In sample A, there are 45 unclassified X-ray-weak quasars, 9 of which have relatively weak emission lines with C IV REW ranging from 16 to 25 Å, 2 of which have 0.1 < Δ(g − i) < 0.2 and visually confirmed redder-than-average continua, and 12 of which are mini-BAL quasars. All of these 45 unclassified X-ray-weak quasars are X-ray detected. Among these quasars, 37 are likely X-ray absorbed with Γ_{eff} values ranging from −1.4 to 1.2, and 7 (3 not included in sample B + C) are potentially X-ray unabsorbed, with their Γ_{eff} values ranging from 1.3 to 2.3. These seven objects are candidates for intrinsically X-ray-weak quasars. The other quasar (included in sample B + C) is undetected in both the soft and hard bands, and thus it is unclear if this object is X-ray absorbed.

### 6. Summary and Future Work

We have investigated systematically the X-ray properties of a large sample of SDSS quasars. We constrained the fraction of X-ray-weak quasars and discussed the possible causes of quasar X-ray weakness. The main points from this work are the following:

1. After removal of BAL and RL quasars, we selected the final sample, or sample A, of 1825 SDSS DR7 and DR10 quasars with Chandra archival X-ray observations (Section 2). We measured their X-ray properties (Section 3), calculated the α_{OX} parameter, and investigated the α_{OX}–L_{2500A} relation (Section 4.1).

2. The Δα_{OX} distribution for sample A has a clear negative tail, suggesting the existence of a population of X-ray-weak quasars. The fraction of X-ray-weak quasars (Δα_{OX} ≤ −0.3) is 5.8% ± 0.7%, and quasars that are X-ray weak by factors of 10 and 20 represent 2.7% ± 0.5% and 1.3% ± 0.3% of the population, respectively. See Section 4.2.

3. We constructed two subsamples (samples B and C), without direct reference to their X-ray properties, that contain 218 DR7 and 208 DR10 quasars, respectively. Both subsamples are composed of X-ray detections only, and the fractions of X-ray-weak quasars among these two subsamples are consistent with those in sample A. See Section 4.3.

4. We note that the fraction of X-ray-weak quasars likely has a luminosity dependence. The fractions derived in this study are mostly applicable to quasar samples sharing similar properties to our SDSS quasars here (Table 1), and extra caution is needed if quoting the fractions for quasars with substantially different luminosities. See Section 5.1.

5. WLQs (C IV REW < 16 Å) represent one population of X-ray-weak quasars, and their X-ray-weak fraction (35±12%) is significantly higher than that of non-WLQs. See Section 5.2.1.

6. Red quasars (Δ(g − i) > 0.2) are likely to be another population of X-ray-weak quasars, and their X-ray-weak fraction (13±5%) is considerably higher than that of normal quasars. See Section 5.2.2.

7. We provide several possible explanations for the X-ray weakness of quasars in the unclassified category: relatively weak C IV emission lines, relatively red optical/UV continua, mini BALs, NALs, and X-ray..
variability. We consider X-ray variability the most plausible explanation; such quasars include quasars that vary strongly in the X-ray band but not in the optical/UV, “changing-look” quasars, and quasars that show BAL disappearance or emergence. See Section 5.2.3.

Further work is needed to improve the results of this study. Deeper radio observations, e.g., with the Very Large Array Sky Survey (e.g., Lacy et al. 2020a, 2020b) will be helpful to discriminate $R \geq 10$ versus $R < 10$ for the optically faint quasars (especially the post-DR7 quasars), thus removing non-RQ objects with possibly enhanced X-ray emission. Deeper X-ray observations, e.g., Chandra observations with typical individual exposure times of $\approx 30$ ks (estimated from the current median exposure time and source counts), are required to better constrain the spectral shapes of the detected sources, thus helping more reliably distinguish between absorbed and unabsorbed quasars.

Additionally, although X-ray–weak quasars constitute only a small fraction of the non-BAL quasar population, they may provide us with new insights into the SMBH disk–corona system and BELR. Deeper X-ray observations, e.g., with the Very Large Array Sky Survey is $\approx$ 3 million erg cm$^{-2}$ s$^{-1}$, are required to assess their physical nature. For example, Chandra observations with exposure times of $\approx 100$ ks will on average yield $\approx 50$ broadband counts for the X-ray–weak quasars in sample B + C.

Our study here will benefit from a larger sample of X-ray quasars to increase the statistical significance of the results and to identify more X-ray–weak quasars. The SDSS Data Release 16 quasar catalog (DR16Q; Lyke et al. 2020) contains 750,426 spectroscopically confirmed quasars. Combining the Chandra archive with the DR16Q will extend the X-ray quasar study to an even larger sample. Furthermore, the XMM-Newton serendipitous source catalogs (e.g., Watson et al. 2009; Rosen et al. 2016) are good complements to the Chandra archival X-ray data. The latest 4XMM-DR9 catalog covers a sky area of 1152 deg$^2$, and contains 810,795 detections comprising 550,124 unique X-ray sources. With an estimated 20,000–25,000 matches in the DR16Q catalog, the 4XMM-DR9 catalog can significantly increase the number of X-ray quasars.

Finally, the extended ROentgen Survey with an Imaging Telescope Array (eROSITA; Merloni et al. 2012), a Russian–German space mission, will discover many more X-ray AGNs and quasars in the near future. Launched on 2019 July 13, eROSITA is performing a medium–depth X-ray all–sky survey over the next four years. eROSITA aims to map the entire sky in the soft X-ray band (0.5–2 keV) at a level $>20$ times more sensitive than the ROSAT all–sky survey, as well as in the hard X-ray band (2–10 keV), which will provide the first imaging all–sky survey at these higher X-ray energies. The 4 yr eROSITA all–sky survey is expected to detect $\approx 3$ million AGNs and quasars. However, the expected sensitivity of the 4 yr all–sky survey is $\approx 1 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ in the soft band (0.5–2 keV), which equals the median 0.5–2 keV flux of sample B + C quasars. The 0.5–2 keV fluxes of the 26 X-ray–weak quasars in sample B + C range from $\approx 1 \times 10^{-16}$ to $4 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$, with median and mean values of

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Appendix

J1457+2218: A Candidate for an Intrinsically X-Ray-weak Quasar

One of the WLQs, J1457+2218, is a good candidate for an intrinsically X-ray–weak quasar. It has 70 broadband counts in the source-extraction region: 47 in the soft band and 23 in the hard band, sufficient for basic spectral fitting. Using the CIAO SPECTRAXTRACT script, we extracted the broadband spectrum of J1457+2218 from a circular region with a radius of 3.3 pixels centered at the X-ray position, corresponding to a 90% encircled-energy fraction. The background spectrum was extracted from an annular region with an inner radius of 18.3 pixels and an outer radius of 53.3 pixels, which corresponds to the source radius plus 15 and 50 pixels, respectively. Note that J1457+2218 is close to a galaxy cluster, MS 1455.0+2232, which is the target of the Chandra observation, and the distance between their centers is 2.0. Thus, the source and background regions of J1457+2218 are likely to be contaminated by the diffuse source. However, because the photon counts in the background region are relatively uniformly distributed and the spectral counts contain only $\approx 1$ background count, the nearby galaxy cluster does not affect our spectral analysis significantly.

We performed spectral fitting using XSPEC v12.9.0 (Arnaud 1996). The C-statistic ($c_{\text{stat}}$) was used given the limited source counts (Cash 1979). We first fit the spectrum with a power-law model modified by only the Galactic absorption (zpows*fabs). The photon index of $\Gamma = 1.6^{+0.4}_{-0.3}$ derived from this spectral fitting is in agreement with $\Gamma_{\text{eff}} = 1.6^{+0.3}_{-0.2}$ (Table 6) derived from the band ratio.

We also fit the spectrum with a power-law model modified by both Galactic absorption and intrinsic absorption at the quasar redshift (zpows*wabs*zwabs). The best-fit values of the photon index and intrinsic absorption column density are $\Gamma = 1.8^{+0.4}_{-0.3}$ and $N_{\text{HI}} = 9.0^{+1.7}_{-0.8} \times 10^{22}$ cm$^{-2}$, respectively. The errors are quoted at a 68% (1σ) confidence level. Figure A1(a) shows the X-ray spectrum of J1457+2218 and the best-fit model. We note that there appears to be excess residuals at rest-frame $\approx 7.6$–8.1 keV. While the current Chandra effective exposure time is 88.4 ks, still deeper X-ray data are required to determine if there is any line emission, which may be due to bluesthifted iron emission. It appears that J1457+2218 does not suffer from strong X-ray absorption. J1457+2218 has $\Delta_{\text{OX}} = -0.30$, which corresponds to an X-ray-weakness factor of $f_{\text{weak}} = 6.1$, and it remains X-ray weak by a factor of 4.7 after being corrected for intrinsic absorption. J1457+2218 is also RI with $R = 42$ and may have

19 http://xmmssc.irap.omp.eu/Catalogue/4XMM-DR9/4XMM_DR9.html
20 http://www.mpe.mpg.de/eROSITA

≈2 × 10$^{-15}$ erg cm$^{-2}$ s$^{-1}$. Thus, the eROSITA all–sky survey will probably be unable to enlarge significantly the sample size or unravel the nature of these exceptionally X-ray–weak quasars identified here.
some jet-linked X-ray emission, which would indicate even weaker intrinsic coronal X-ray emission. The spectral fitting results suggest that J1457+2218 is probably an intrinsically X-ray–weak WLQ like PHL 1811. Figure A1(b) shows the optical/UV spectra of J1457+2218 and PHL 1811 for comparison. J1457+2218 has overall stronger emission line than PHL 1811; for example, the SDSS (BOSS) C IV REW is 22.0 Å (15.5 Å), while it is 4.7 Å for PHL 1811.

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![Figure A1](https://orcid.org/0000-0003-3349-4855)

(a) Chandra broadband (0.5–7 keV) spectrum of J1457+2218 (blue) and the best-fit model with both Galactic and intrinsic absorption (red). The spectrum was binned to a minimum of five counts per bin for display purposes. The inset shows the best-fit values of $\Gamma$ and intrinsic $N_H$ (magenta), and contours of $\Gamma$ vs. $N_H$ at confidence levels of 68% (blue), 90% (green), and 99% (red), respectively. The bottom panel is the data divided by the model. (b) SDSS DR7 spectrum (red) and BOSS DR10 spectrum (blue) of J1457+2218. The gray curve shows the PHL 1811 spectrum for comparison.
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