X-RAY EMISSION FROM RADIO-QUIET QUASARS IN THE SLOAN DIGITAL SKY SURVEY
EARLY DATA RELEASE: THE $\alpha_{\text{OX}}$ DEPENDENCE UPON ULTRAVIOLET LUMINOSITY

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ABSTRACT

We investigate the X-ray properties of the color-selected, radio-quiet quasars (RQQs) in the Sloan Digital Sky Survey (SDSS) Early Data Release using ROSAT, Chandra, and XMM-Newton data. In the 0.16–6.28 redshift range, 136 RQQs have X-ray detections (69 from the ROSAT All-Sky Survey, RASS), while for 70 RQQs X-ray upper limits are obtained. The well-defined selection method used by the SDSS, coupled with the tight radio constraints from the FIRST and NVSS surveys, allows us to define a representative sample of optically selected RQQs whose broadband spectral energy distributions (characterized by means of the optical–to–X-ray spectral index, $\alpha_{\text{OX}}$) can be studied as a function of rest-frame ultraviolet (UV) luminosity and redshift. A partial correlation analysis applied to the SDSS sample (including the upper limits, but excluding the biased subsample of RASS detections) shows that $\alpha_{\text{OX}}$ is a function of rest-frame UV luminosity (i.e., $\alpha_{\text{OX}}$ steepens at high UV luminosities); this correlation is significant at the 3.7 $\sigma$ level. We do not detect a highly significant redshift dependence of $\alpha_{\text{OX}}$. We also find a significant (7.8 $\sigma$ level) correlation between UV and X-ray luminosity. This correlation, parameterized by $L_X \propto L_{\text{UV}}^{0.75\pm0.06}$, extends previous results to the highest redshifts.

Key words: galaxies: active — galaxies: nuclei — quasars: general — surveys — X-rays

On-line material: color figure, machine-readable table

1. INTRODUCTION

To date, many studies have focused on the dependence of quasar ultraviolet–to–X-ray spectral energy distributions [often characterized by means of the spectral index $\alpha_{\text{OX}} = 0.384 \log (L_{2 \text{keV}}/L_{2500 \text{Å}})$] on luminosity and cosmic time. Quasars are known to exhibit strong luminosity evolution in the optical band (e.g., Boyle et al. 1994, 2000) and perhaps luminosity-dependent density evolution in the X-ray band (e.g., Miyaji, Hasinger, & Schmidt 2000; La Franca et al. 2002). A dependence of $\alpha_{\text{OX}}$ on redshift would suggest different evolution in the optical and X-ray regimes.

Most previous studies agree that $\alpha_{\text{OX}}$ is only marginally dependent upon redshift, the primary dependence of $\alpha_{\text{OX}}$ being on 2500 Å luminosity (e.g., Avni & Tananbaum 1982, 1986; Marshall et al. 1984; Kriss & Canizares 1985; Tananbaum et al. 1986; Anderson & Margon 1987; Wilkes et al. 1994; Pickering, Impey, & Foltz 1994; Avni, Worrall, & Margon 1995). The only significant exception has been recently reported by Bechtold et al. (2002), who claimed that $\alpha_{\text{OX}}$ depends primarily upon redshift. These studies were generally characterized by heterogeneous selection criteria or covered limited ranges of redshift or luminosity. Most investigations included both radio-quiet quasars (RQQs) and radio-loud quasars (RLQs). The X-ray properties of these two subclasses of the quasar population are now well known to be different, with the RLQ emission often being dominated by the jets and enhanced by boosting (e.g., Wilkes & Elvis 1987; Worrall et al. 1987; Cappi et al. 1997). As discussed in § 4.1.2.2 of Anderson (1985) and Appendix A of Anderson & Margon (1987), analyses of heterogeneous samples (such as RQQs and RLQs combined) with survival analysis techniques can lead to misleading results. Moreover, many previous samples also included broad absorption line quasars (BALQSOs). Recent studies (e.g., Gallagher et al. 2001, 2002; Green et al. 2001) have shown that, although BALQSOs are probably characterized by the same underlying X-ray continua as the majority of the quasar population, their X-ray emission is often depressed by large amounts of intrinsic absorption. This effect appears to apply to both low- and high-redshift BALQSOs (e.g., Brandt, Laor, & Wills 2000; Brandt et al. 2001; Vignali et al. 2001a; Gallagher et al. 2002). Although BALQSOs do not contribute greatly to the overall optically selected quasar population (~10%–15%; e.g., Weymann et al. 1991; § 8.1 of Brandt et al. 2000; Tolea, Krolik, & Tsveytov 2002), their inclusion can provide an “artificial” steepening of $\alpha_{\text{OX}}$, as well as a larger, spurious scatter in any correlation study involving this spectral index (see Figure 4.1.2.2a and the associated text in Anderson 1985).

Motivated by these considerations, we have started a project to investigate the dependence of $\alpha_{\text{OX}}$ upon UV luminosity and redshift using the quasars discovered by the Sloan Digital Sky Survey (SDSS; York et al. 2000) and currently published mainly in the Early Data Release (EDR; Stoughton et al. 2002) quasar catalog (Schneider et al. 2002). The SDSS provides a large and well-defined sample of optically selected quasars with a broad range in UV luminosity and redshift, suitable for such studies and to break degeneracies in the luminosity-redshift parameter space. We have focused on the RQQs, since they make up the bulk of the quasar population (~85%–90%; e.g., Stern et al. 2000; Ivezić et al. 2002) and are not strongly affected by jet emission or boosting effects. For most of the objects, X-ray information has been obtained through analysis of ROSAT.

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2 Available at http://archive.stsci.edu/sdss/quasars/edrqso.cat.
data. For the highest redshift (i.e., $z > 4$) quasars, however, we have also exploited the excellent capabilities of *Chandra* and *XMM-Newton*.

Throughout this paper, we adopt $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ in a $\Lambda$-cosmology with $\Omega_M = 0.3$ and $\Omega\Lambda = 0.7$ (e.g., Line- weaver 2001). Note that most of the $\alpha$-$\log L_{2500\AA}$ correlation papers previously cited used a $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.0$ cosmology, which provides larger luminosities by factors of $\approx 2.0$–6.5 in the redshift range $\approx 0$–6.3.

### 2. THE SAMPLE: THE SDSS EARLY DATA RELEASE QUASAR CATALOG

The SDSS EDR (Stoughton et al. 2002) contains 462 deg$^2$ of imaging data in five bands (designated $u$, $g$, $r$, $i$, and $z$; Fukugita et al. 1996; Gunn et al. 1998) and 54,008 spectra in the same area. The data were acquired in three regions: along the celestial equator in the southern Galactic sky, along the celestial equator in the northern Galactic sky, and in a region overlapping the *SIRTF* First Look Survey. The SDSS EDR catalog of quasars consists of 3814 objects (3000 discovered by the SDSS) selected through a multicolor technique (similar to that described by Richards et al. 2002) down to magnitude limits of $i \approx 19$ and $i \approx 20$ for quasars below and above $z \approx 3$, respectively (Stoughton et al. 2002), with an overall expected completeness higher than 90%. In addition to the multicolor selection, a small percentage ($\approx 0.5\%$) of SDSS targets were unresolved objects brighter than $i \approx 19$ that were coincident with FIRST radio sources (Becker, White, & Helfand 1995). The EDR quasars were selected in three stripes (each $\approx 2.5$ deg wide) over a slightly larger area (494 deg$^2$) than that covered by imaging observations because some additional “interesting” fields were included (Stoughton et al. 2002). These quasars have at least one emission line with a FWHM larger than 1000 km s$^{-1}$, luminosities higher than $M_i = -23$ (for $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$, $q_0 = 0.5$) and highly reliable redshifts ranging from 0.15 to 5.03. The EDR quasars used in this paper are those having the “quasar target flag” set to 1 in the EDR quasar catalog (col. [22] in the quasar catalog; see § 4 of Schneider et al. 2002). In this paper, the SDSS EDR sample of quasars is extended to higher redshifts by including all of the published SDSS quasars up to $z = 6.28$ (e.g., Fan et al. 2001a) to place better constraints on the relevant correlations. The additional quasars represent only a small addition to the main EDR sample ($\approx 2.6\%$); since they have been selected using a multicolor selection technique, we do not expect any significant bias to be introduced into the analysis.

#### 2.1. Selection of RQQs

The minority of EDR quasars selected based on their detection by *FIRST* (see § 2) were immediately excluded from our study. Then from the color-selected SDSS quasars, we have excluded all the RLOs, i.e., those quasars having a radio-loudness parameter, $R$, larger than 10 (e.g., Kellermann et al. 1989). Radio flux densities at 1.4 GHz have been obtained either from *FIRST* or from NVSS (Condon et al. 1998), down to typical $3\sigma$ upper limits of 0.5 and 1.5 mJy, respectively. All of the quasars with X-ray coverage also have NVSS/FIRST coverage. Quasars characterized by loose radio-loudness upper limits (i.e., $R \leq 18$; only five in the sample of 206 SDSS quasars used in the following analysis) have been assumed to be radio-quiet. Within the sample of SDSS quasars with X-ray coverage, the fraction of RQQs is $\approx 90\%$, which is in good agreement with previous estimates for optically selected quasars (e.g., Stern et al. 2000) and suggests that assuming the quasars with loose radio-loudness upper limits to be radio-quiet is reasonable.

#### 2.2. Optical Magnitudes

The magnitudes reported in the EDR catalog are generally accurate to 0.05 mag or better. To derive absolute luminosities for the SDSS quasars, the catalog magnitudes were first corrected for Galactic absorption using the *COBE* DIRBE maps of Schlegel, Finkbeiner, & Davis (1998) and the scaling laws for the five SDSS filters reported in Schneider et al. (2002). The composite quasar spectrum presented in Vanden Berk et al. (2001), which was constructed using SDSS spectra of over 2000 quasars, was used to convert the broadband $ugriz$ measurements to flux densities at rest wavelengths of 2500 Å (required for $\alpha$ measurements) and 4400 Å (required to compute the radio-loudness parameter); this method accounts for emission lines as they pass through the SDSS filters. The offsets for both the rest-wavelength 2500 and 4400 Å flux densities as a function of redshift were calculated for each of the SDSS filters, using interpolation whenever possible. For example, if the observed wavelength of rest-frame 2500 Å occurred between the $g$ and $r$ filters, the value of the 2500 Å flux density was calculated using the relations for both the $g$ and $r$ filters, and the final measurement was the weighted average of the 2500 Å flux densities, weighted by the relative distances of 2500(1 + $z$) Å from the central wavelengths of the $g$ and $r$ filters. If rest-wavelength 1280 Å occurred redward of the central wavelength of a filter, that filter was not used in the calculation, due to the large dispersion in the relations introduced by the presence of the Ly$\alpha$ emission line and the Ly$\alpha$ forest. If the observed-frame wavelength of the desired region of the spectrum was larger than the effective wavelength of the reddest filter, the relation for the reddest filter was used.

### 3. THE X-RAY DATA: DATA REDUCTION AND ANALYSIS

#### 3.1. The $z < 4$ Sample: ROSAT Observations

The EDR quasar catalog was cross-correlated with archival ROSAT data (pointed Position Sensitive Proportional Counter [PSPC], pointed High-Resolution Images [HRI], and the ROSAT All-Sky Survey [RASS]). We used only the central regions (20' radius) of the ROSAT PSPC and HRI detectors, where the sensitivity is highest and the PSPC window support structure does not affect source detection. This maximizes the probability of detecting faint sources. In cases of multiple observations of the same SDSS quasar, we chose the one with the best combination of off-axis angle and exposure time. Approximately 3.2% of the EDR area is covered by ROSAT pointed observations (considering only the inner 20' of the ROSAT field of view, 37 PSPC fields [two largely overlapping] and 11 HRI fields; see...
Source detection was performed in the 0.5–2 keV band for the PSPC and in the full band for the HRI, since no spectral information is available for the HRI. A conservative matching radius of 40 arcmin was used to take into account the broadening of the point-spread function at large off-axis angles.5

The pointed ROSAT PSPC and HRI data have been analyzed with the MIDAS/EXSAS package (Zimmermann et al. 1998). The sources have been detected by running the local detection algorithm LDETECT, the bicubic spline fit to the background map, and the map detection algorithm MDETECT. The detection threshold of these algorithms was set at a likelihood of \( L = -\ln(P_e) = 6 \), corresponding to a probability \( P_e \) on the order of 2.5 \( \times 10^{-3} \) that the observed number of photons in the source cell is produced entirely by a background fluctuation (corresponding to the \( \approx 3 \sigma \) detection level; Cruppdace, Hasinger, & Schmitt 1988). In the present sample, the sources detected by the ROSAT PSPC (HRI) have typical offsets of less than 15′–20′ (10′) from their optical positions, which are accurate to within 0′.2 (Schneider et al. 2002). This range of offsets is consistent with the values found recently by Vignali et al. (2001b) for faint, hard X-ray–selected sources in PSPC/HRI fields. All of the sources were inspected by eye to verify that they are not spurious fluctuations due to enhanced local background. Our previous experience (e.g., Vignali et al. 2001b) suggests that the combination of detection algorithms described above is quite effective at minimizing the number of spurious detections. We expect only \( \approx 0.3 \) false sources in our sample due to background fluctuations adopting the detection threshold reported above. Assuming the integral 0.5–2 keV source counts of Hasinger et al. (1998), we conservatively expect \( \leq 2 \) spurious associations within the present sample of ROSAT-detected sources.

The background-subtracted, vignetting-corrected source counts were determined using the maximum likelihood method (MAXLIK). For the sources not detected in the ROSAT pointed observations, 3 \( \sigma \) X-ray upper limits were computed using the SOSTA task in the XIMAGE package (Giommi et al. 1992) and an average value for the background close to the quasar position.

The same matching radius was used for the RASS data (see, e.g., Voges et al. 1999) in the 0.1–2.4 keV band with a slightly higher detection threshold \([L = -\ln(P_e) = 7, \text{the minimum available using the ROSAT Source Browser}]^6\). The average exposure time for the quasars detected in the RASS is \( \approx 1.2 \) ks.

### 3.1.1. ROSAT Results

The results of the cross-correlation of the SDSS EDR quasars with archival ROSAT data are presented in Table 1. None of the SDSS EDR quasars at \( z > 4 \) lies in the inner 20′ of a ROSAT field. We found 54 X-ray–detected RQQs in pointed PSPC fields, seven in pointed HRI fields, and 69 in the RASS. The numbers of upper limits were 42 and 25 for the PSPC and HRI, respectively. Only a small fraction (\( \approx 4.7\% \)) of the ROSAT pointed observations were targeting SDSS quasars (five detections and one upper limit); the relevant quasars are listed in Table 2 with a value of 0′′ for the off-axis angle. The exclusion of the ROSAT targets from the following analyses does not change materially any of the results presented below. A plot of the number of counts from ROSAT-detected quasars as a function of redshift is shown in Figure 2. Most of the X-ray detections are too

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5 See ftp://ftp.xray.mpe.mpg.de/rosat/catalogues/1rxp/wga_rosatsrc.html.

6 Available at http://www.xray.mpe.mpg.de:80/cgi-bin/rosat/src-browser.

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**Fig. 1.** — ROSAT coverage of the SDSS EDR quasars (small points) with pointed PSPC and HRI observations (circles of radius 20′ in sky coordinates). The stars indicate the SDSS EDR RQQs used in this work. The small points in some circles are RLQs, which were not used in this work.

**Fig. 2.** — Number of counts (corrected for vignetting) in the 0.5–2 keV band for ROSAT–detected SDSS RQQs as a function of redshift. Triangles, squares, and circles represent pointed PSPC, pointed HRI, and RASS detections, respectively.
found seven BALQSOs; one was detected by ROSAT in the 0.5–2 keV band (seven quasars at redshift analysis. Ten quasars have less than 10 counts in the 0.5–2 keV band; all observed by the PSPC). All of these faint objects satisfy the detection threshold because of the high sensitivity generally observed by the PSPC and five by the RASS; three at $z < 2$ were not. Unfortunately, no information about the presence of broad UV absorption features is available for six of these sources after visual inspection, and in two out of five cases we were able to confirm the source’s existence by analyzing an additional ROSAT PSPC observation (in the other cases, no additional pointed observations were available).

Among the quasars with pointed ROSAT coverage, we found seven BALQSOs; one was detected by ROSAT and six were not. Unfortunately, no information about the presence of bright UV absorption features is available for $z < 1.5$ quasars due to the wavelength range of the SDSS spectrograph (3800–9200 Å; York et al. 2000). The relatively small fraction of BALQSOs within optically selected samples ($\approx 10\%$–$15\%$; e.g., Weymann et al. 1991; Brandt et al. 2000; Tolea et al. 2002) suggests that BALQSOs probably do not significantly contribute to the average properties of the present sample at $z \lesssim 1.5$. We have searched in the NASA Extragalactic Database (NED) for published UV spectra of the SDSS quasars at $z \lesssim 1.5$. A small fraction (below 1%) of the low-redshift SDSS quasars have UV coverage, and none of these shows broad absorption features. In §§4.3 and 4.4, we will statistically estimate the impact of BALQSOs on $\alpha_{ox}$ determinations at $z \lesssim 1.5$.

3.2. The $z > 4$ Sample: Chandra and XMM-Newton Observations

All but one of the $z > 4$ SDSS quasars in the X-ray sample have been observed by Chandra, the only exception being the $z = 5.74$ quasar (Fan et al. 2000b) detected by XMM-Newton (Brandt et al. 2001). This quasar has recently been detected by the X-ray observations of this work.

### Table 1: Numbers of SDSS RQQs in ROSAT, Chandra, and XMM-Newton Observations

| Redshift Range | ROSAT | Chandra | XMM-Newton |
|----------------|-------|---------|------------|
|                | PSPC  | HRI     | ACIS       | EPIC     |
| $z < 2$        | D     | UL      | D          | UL       | D          |
| $2 < z < 4$    | 11    | 10      | 2          | 6        | 1          |
| $z > 4$        | ...   | ...     | ...        | ...      | ...        |

**Note.**—"D" indicates the number of X-ray detections, while “UL” indicates the number of upper limits.

### Table 2: Properties of the SDSS Quasars with X-Ray Observations

| SDSS Object               | Alt. Name$^a$ | $z$ | $A_{B1450(1+z)}$ | $M_B$ | $L_{2500\,\lambda}^b$ | $f_{5.2-2keV}^{c,d}$ | $f_{2keV}^{c,b}$ |
|---------------------------|---------------|-----|-----------------|------|---------------------|---------------------|-----------------|
| 000710.01+05329.0...........| LBQS 0004+0036 | 0.316 | 17.67 | $-23.95$ | 5.07 | 30.10 | 8.85 | 1.74 |
| 000834.71+003156.1..........| LBQS 0006+0015 | 0.263 | 18.26 | $-22.70$ | 2.94 | 29.70 | 3.21 | 0.604 |
| 001257.25+011527.3...........| LBQS 0019-0000 | 0.504 | 18.90 | $-23.31$ | 1.59 | 30.02 | 3.21 | 0.721 |
| 002209.95+001629.3...........| LBQS 0020+0058 | 0.728 | 18.57 | $-24.60$ | 2.31 | 30.50 | 2.92 | 0.754 |

**Notes.**—Table 2 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content. Luminosities are computed using $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$. The upper limits are at the 3 $\sigma$ level. BALQSOs are flagged in the first column.

$^a$ Alternative name as reported in the SDSS EDR catalog.

$^b$ Rest-frame flux density in units of $10^{-27}$ ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ (at 2500 Å) and $10^{-30}$ ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ (at 2 keV).

$^c$ Rest-frame luminosity density (ergs s$^{-1}$ Hz$^{-1}$).

$^d$ Galactic absorption-corrected flux in the observed 0.5–2 keV band in units of $10^{-13}$ ergs cm$^{-2}$ s$^{-1}$.

$^e$ Observed-frame 1.4 GHz flux density either from FIRST or NVSS (in millijansky).

$^f$ Radio-loudness parameter, defined as $R = f_{1.4GHz}/f_{4000\lambda}$ (rest frame; e.g., Kellermann et al. 1989). The rest-frame 5 GHz flux density is computed from the observed-frame 1.4 GHz flux density assuming a radio power-law slope of $\alpha = -0.8$, with $f_{1.4} \propto \nu^\alpha$.

$^g$ X-ray instrument used in the analysis: (R) ROSAT All-Sky Survey; (P) pointed ROSAT PSPC; (H) pointed ROSAT HRI; (C) Chandra ACIS-S; (X) XMM-Newton EPIC.

$^h$ Exposure time (in seconds).

$^i$ Off-axis angle (in arcminutes).
been revealed to be a BALQSO (Maiolino et al. 2001; Goodrich et al. 2001). The Chandra results reported in this paper have been taken from Vignali et al. (2001a; five SDSS RQQs, two of which are X-ray–undetected BALQSOs) and Brandt et al. (2002; two SDSS RQQs). Chandra data for one additional SDSS RQQ have been retrieved from the archive (also published by Bechtold et al. 2002). All of the Chandra sources were observed with the back-illuminated ACIS-S/S3 CCD (Garmire et al. 2002). Source detection was carried out with WAVDETECT (Freeman et al. 2002). For each image, we calculated wavelet transforms (using a Mexican hat kernel) with wavelet scale sizes of 1, 1.4, and 2 pixels using a false-positive probability threshold of $10^{-6}$ (see Vignali et al. 2001a for further information about the Chandra reduction and detection processes).

To increase the number of quasars at $z > 4$ populating the high-luminosity tail of the luminosity function, and therefore to place stronger constraints on the parameters involved in this study, we will also include in the analysis 13 luminous RQQs taken from the Palomar Digital Sky Survey (hereafter referred to as PSS; Djorgovski et al. 1998) which have been observed by Chandra (Vignali et al. 2001a, 2003). Twelve of these objects are detected in the soft (0.5–2 keV) X-ray band. Given their high luminosities, these objects are sufficiently bright that any quasars of this class that fall in the SDSS survey area will be included in the SDSS spectroscopic survey (indeed, many PSS quasars have already been recovered by the SDSS; see Schneider et al. 2002 and references therein). Therefore, we do not expect to introduce biases by including PSS quasars in our otherwise pure SDSS sample. The critical results below will be given both with and without inclusion of the PSS quasars.

### 3.2.1. Chandra and XMM-Newton Results

A summary of the Chandra and XMM-Newton results for $z > 4$ SDSS RQQs is presented in Table 1. We found six X-ray–detected SDSS RQQs and three upper limits, two of which are associated with BALQSOs (see Vignali et al. 2001a for a detailed discussion). The last X-ray–undetected quasar is peculiar; its optical spectrum is characterized by a lack of emission lines (Fan et al. 1999, 2000a).

#### 3.3. Count Rate–to–Flux Conversion

All of the X-ray fluxes reported in this paper have been converted into the observed 0.5–2 keV band and corrected for Galactic absorption. The count rate–to–flux conversion was computed using the Portable, Interactive, Multi-Mission Simulator (PIMMS, Version 3.2c; Mukai 2001) software for a power-law photon index\(^7\) of $\Gamma = 2$ and Galactic absorption (Dickey & Lockman 1990). Samples of $z \approx 0$–2 RQQs are well fitted in the 2–10 keV band by power-law continua with $\Gamma = 1.7$–2.3 (e.g., George et al. 2000; Mineo et al. 2000; Reeves & Turner 2000). Although there have been claims of a possible flattening of X-ray spectral continua at $z \approx 2$ (e.g., Vignali et al. 1999; Blair et al. 2000), the assumption of a flatter slope ($\Gamma = 1.5$) has only a few percent effect ($\approx \pm 1\%–2\%$) on the derived fluxes. In the same manner, assuming a steeper power-law slope ($\Gamma = 2.5$) has a few percent effect on the derived fluxes. It must also be kept in mind that, given the large redshift range of the SDSS quasars used here, we are not sampling the same rest-frame X-ray bandpass for the entire SDSS sample; therefore, the assumption of a single power-law model for the count rate–to–flux conversion may be too simplistic. However, although the direct spectral information available for $z > 2$ high-luminosity RQQs is still limited, there are indications that quasars at the highest redshifts are also well parameterized by $\Gamma \approx 2$ power-law X-ray continua (e.g., Dewangan et al. 2002; Page et al. 2002; Vignali et al. 2003).

The observed-frame 0.5–2 keV flux distribution for our sample is plotted in Figure 3. Most of the X-ray brightest objects have been detected by the RASS (thick solid line).

#### 3.4. SDSS RQQs Observed in the X-Ray Band

The combined SDSS, ROSAT, Chandra, and XMM-Newton data allow a systematic study of the ultraviolet–to–X-ray properties of SDSS RQQs in the redshift range $z = 0.16$–6.28. A total of 206 RQQs have X-ray information: 136 have been detected, while for 70 RQQs 3 $\sigma$ upper limits have been derived. Systematic cross-calibration errors might be present when data from different X-ray instruments are analyzed. However, to date, we have no indication of any ROSAT versus Chandra cross-calibration problems (T. Gokas 2002, private communication).\(^8\) The principal optical, X-ray, and radio information for the SDSS RQQs with X-ray coverage is summarized in Table 2.\(^9\)

\(^7\) $\Gamma = -\alpha + 1$; $N(E) \propto E^{-\Gamma}$, where $N(E)$ has units of photons cm$^{-2}$ keV$^{-1}$ s$^{-1}$.

\(^8\) See also http://cxc.harvard.edu/cal/Links/Acis/acis/ Presentations/cross_cal/wa2-snowden.

\(^9\) This table is also available at http://www.astro.psu.edu/users/niel/papers/papers.html.
luminosity density distributions of the X-ray–detected SDSS quasars (shaded area) with the overall sample of SDSS quasars with X-ray information (thin solid line). The thick line shows the SDSS RQQs detected by the RASS, most of which are at $z < 1.5$. The sample has a fairly high fraction of X-ray detections ($\approx 49\%$ if only pointed observations are taken into account). Among the 206 SDSS RQQs, 11 objects at low redshift are optically resolved (Schneider et al. 2002). They do not populate a particular region in the optical–X-ray luminosity space, suggesting that the emission from their host galaxies is likely to be negligible.

4. BROADBAND PROPERTIES OF SDSS QUASARS

One of the main goals of this paper is to study the broadband properties of SDSS RQQs, parameterized by the optical–to–X-ray spectral index \( \alpha_{\text{ox}} = \log \left( \frac{f_{2\text{ keV}}}{f_{2500\text{ Å}}} \right) / \log \left( \frac{\nu_{2\text{ keV}}}{\nu_{2500\text{ Å}}} \right) \), as a function of rest-frame UV luminosity density and redshift. Working with nonsimultaneous UV and X-ray data will have some effects on the derived individual \( \alpha_{\text{ox}} \) values, but since our samples are fairly large we do not expect significant biases when the samples are considered as a whole. Since most of the papers cited in § 1 have focused on the relationship between rest-frame 2500 Å luminosity density (hereafter referred to as \( L_{\text{UV}} = \log L_{2500\text{ Å}} \)) and rest-frame 2 keV luminosity density (hereafter referred to as \( L_X = \log L_{2\text{ keV}} \)), we will address this issue as well. The choice of using luminosity densities instead of flux densities is based on several arguments, as stated in Kembhavi, Feigelson, & Singh (1986), and generally provides more robust results. However, this choice introduces a possible bias into the analysis, since luminosity is strongly correlated with redshift in flux-limited samples. It is therefore crucial to estimate the influence of this effect on the correlations in order to draw reliable conclusions about true physical relationships. In this paper, this has been achieved with the partial correlation analysis technique developed for use with censored data (Akritas & Siebert 1996).

4.1. The Technique: Partial Correlation and Regression Analysis

A partial correlation analysis investigates the correlation of two variables while controlling for (holding constant) a third or additional variables. Partial correlation analysis requires meeting all of the assumptions of Pearsonian correlation, e.g., the linearity of the relationships (including that between the original variables and the control variable). The method used in this paper is that described by Akritas & Siebert (1996); this allows one to apply partial correlation to censored data and to assign a significance level to the resulting correlation coefficient based on the Kendall \( \tau \)-statistic (Kendall 1970). When a significant (at the \( \geq 3\sigma \) confidence level) correlation is found according to the partial correlation analysis, its basic parameters are quantified via regression analysis, taking into account upper limits. For this purpose, we have used the ASURV software package Rev 1.2 (LaValley, Isobe, & Feigelson 1992), which implements the survival analysis methods presented in Feigelson & Nelson (1985) and Isobe, Feigelson, & Nelson (1986). We used the EM (estimate and maximize) regression algorithm (Dempster, Laird, & Rubin 1977) and the Buckley-James (Buckley & James 1979) regression method.

4.2. The ROSAT Sample Used in the \( \alpha_{\text{ox}} \) Study

Among the SDSS RQQs with ROSAT coverage, in the \( \alpha_{\text{ox}} \) study, we have used only the 128 RQQs covered by pointed PSPC and HRI observations. As shown in Figure 3, the quasars detected by the RASS are strongly concentrated at bright X-ray fluxes, with most of the sources being brighter than $10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ in the observed-frame 0.5–2 keV band. Although the RASS covers 99.8% of the sky,
typical exposure times are \(\approx 300\text{–}400\) s for most of the fields, which are not suitable for providing useful constraints on \(\alpha_{\text{ox}}\) for our sample. Including both the pointed and RASS data (detections and upper limits) in the \(\alpha_{\text{ox}}\) survival analyses below would likely lead to spurious results, since our sample would be dominated by weak RASS upper limits and would thus suffer from severe pattern censoring problems (see § 4.1.2.1 of Anderson 1985 and Appendix A of Anderson \\& Margon 1987).

The \(\alpha_{\text{ox}}\) distribution of SDSS RQQs (excluding the RASS detections) is shown in Figure 5 (the shaded area indicates the \(\alpha_{\text{ox}}\) values for X-ray–detected quasars). Taking into account upper limits using ASURV, the average \(\alpha_{\text{ox}}\) is \(-1.65 \pm 0.02\). Note, however, that a dependence of \(\alpha_{\text{ox}}\) upon luminosity is likely present (see § 4.4).

One object in our sample, SDSSp J030422.39+002231.7 at \(z = 0.638\), is characterized by a notably steep \(\alpha_{\text{ox}}\) (\(-2.01\)) which suggests it could be a BALQSO or mini-BALQSO (e.g., Brandt et al. 2000). Its optical spectrum is quite blue and shows no obvious absorption near Mg ii. However, the \([\text{O}] \text{ii}\) 5007 Å line is quite weak, and the \(\text{Fe} \text{ii}\) emission-line blends are strong (G. Richards 2002, private communication). These properties have been seen from many low ionization BALQSOs and other soft X-ray–weak quasars (e.g., Boroson \\& Meyers 1992; Turnshek et al. 1997; Laor \\& Brandt 2002).

### 4.3. The Effect of Unknown BALQSOs at \(z \lesssim 1.5\) on \(\alpha_{\text{ox}}\) Measurements

As mentioned in § 3.1.1, at \(z \lesssim 1.5\) it is not possible to identify BALQSOs among the quasars from SDSS spectra. However, their importance in average \(\alpha_{\text{ox}}\) determinations can be estimated statistically. Given the high fraction of X-ray–undetected BALQSOs at \(z > 1.5\) (80\%) and the general evidence that BALQSOs have strongly depressed X-ray emission in the 0.5–2 keV band (see § 1), we have randomly removed from the \(z < 1.5\) subsample (69 RQQs with 39 X-ray detections) a variable number (10\%–15\% of this subsample) of X-ray nondetections. Taking into account the upper limits using ASURV, the average \(\alpha_{\text{ox}}\) at \(z < 1.5\) is \(\langle \alpha_{\text{ox}} \rangle = -1.61 \pm 0.03\). By randomly excluding some of the X-ray nondetections as previously described, we obtain \(\langle \alpha_{\text{ox}} \rangle = -1.58 \pm 0.03\), close to the previous value. It must be kept in mind that some BALQSOs could be detected at \(z < 1.5\); therefore, the previous average value of \(-1.58\) would represent a conservative estimate.

### 4.4. \(\alpha_{\text{ox}}\) versus Redshift and 2500 Å Luminosity Density

The \(\alpha_{\text{ox}}\) distributions as a function of redshift (Fig. 6a) and 2500 Å luminosity density (Fig. 7a) are characterized by large scatter, which prevents one from easily identifying a trend. To shed light on this issue, we averaged the \(\alpha_{\text{ox}}\) values in redshift (Fig. 6b) and luminosity (Fig. 7b) bins taking into account the upper limits. The flat \(\alpha_{\text{ox}}\) value found in the redshift range \(3 < z < 4\) is likely to be due to the small number of objects (eight RQQs, five of which are nondetections). A trend of decreasing \(\alpha_{\text{ox}}\) as a function of redshift and luminosity can be seen in both distributions, although it is not possible to determine which anticorrelation is the most important one or to quantify the significance without applying partial correlation analysis. It must be kept in mind that a certain degree of anticorrelation is expected between \(\alpha_{\text{ox}}\) and log \(L_{2500}\), given the presence of the UV luminosity term in the \(\alpha_{\text{ox}}\) formula (see § 4.5 for further discussion).

The measured values of \(\alpha_{\text{ox}}\) show no strong dependence upon redshift (2.1 \(\sigma\); 1.7 \(\sigma\) when the BALQSOs are removed from the analysis; see Table 3) from the partial correlation analysis. We also searched for possible \(\alpha_{\text{ox}}\)-redshift dependencies in individual redshift/luminosity bins, but found none. The inclusion of the 13 PSS quasars (see § 3.2; open squares in Fig. 6a) provides a slightly, but not sufficiently, better significance of the above anticorrelation (2.8 \(\sigma\); 2.3 \(\sigma\) when the BALQSOs are removed).

Applying the partial correlation analysis, we find that the \(\alpha_{\text{ox}}-L_{UV}\) anticorrelation (hereafter parameterized by the equation \(\alpha_{\text{ox}}=A(L_{UV} + B)\)) is significant at the 3.7 \(\sigma\) level (3.4 \(\sigma\) level) when the BALQSOs are included (excluding) in the analysis (see Table 3). According to the EM regression, the parameters of this relationship are

\[
A_1 = -0.11 \pm 0.02, \quad B_1 = 1.85 \pm 0.69
\]

including BALQSOs and

\[
A_1 = -0.10 \pm 0.02, \quad B_1 = 1.32 \pm 0.70
\]

excluding BALQSOs. The first parameterization is shown in

### Table 3

| Sample Name                        | \(\alpha_{\text{ox}}-z\) | \(\alpha_{\text{ox}}-L_{UV}\) |
|-----------------------------------|--------------------------|-------------------------------|
| SDSS only, with BALQSOs           | 2.1 \(\sigma\)           | 3.7 \(\sigma\)                |
| SDSS only, without BALQSOs        | 1.7 \(\sigma\)           | 3.4 \(\sigma\)                |
| SDSS and PSS, with BALQSOs        | 2.8 \(\sigma\)           | 3.8 \(\sigma\)                |
| SDSS and PSS, without BALQSOs     | 2.3 \(\sigma\)           | 3.9 \(\sigma\)                |
Figure 7a as a dashed line. Similar values are found using the Buckley-James regression method. Using the same approach described in § 4.3, we evaluated the impact of possible unknown BALQSOs in the partial correlation analysis by randomly removing ≈10% of the X-ray nondetections at $z < 1.5$. The $\alpha_{\text{ox}}-l_{\text{UV}}$ anticorrelation is slightly more significant after this procedure. The $\alpha_{\text{ox}}-l_{\text{UV}}$ anticorrelation becomes slightly more significant (3.8 $\sigma$) after the inclusion...
of the PSS quasars in the analysis (Fig. 7a, open squares) with similar best-fit parameters. Our finding above that $\alpha_{\text{ox}}$ depends primarily on $l_{\text{UV}}$ is consistent with the fact that the $\alpha_{\text{ox}}$ dependence upon $l_{\text{UV}}$ in Figure 7b appears somewhat stronger than the $\alpha_{\text{ox}}$ dependence upon redshift in Figure 6b. Given the dependence of $\alpha_{\text{ox}}$ upon $l_{\text{UV}}$, the assumption of the same $\alpha_{\text{ox}}$ value regardless of the UV luminosity density of a quasar may imply up to a factor of $\approx 3$ error in estimating its soft X-ray flux.

It is worth noting that $\approx 5\%$–$10\%$ of $z \approx 4$–$6$ quasars may experience a factor $\approx 2$ magnification due to gravitational lensing (e.g., Wyithe & Loeb 2002; Comerford, Haiman, & Schaye 2002), assuming the SDSS luminosity function reported by Fan et al. (2001b) for $M_B < -26$ SDSS quasars $[\phi(L) \propto L^\beta$, with $\beta \approx -2.5]$. For steeper luminosity functions, the fraction of high-redshift lensed quasars may increase to $\approx 30\%$ (e.g., Wyithe & Loeb 2002). Such an effect will confuse studies of the dependence of $\alpha_{\text{ox}}$ (which should not be changed by lensing, unless the UV and X-ray luminosities are magnified differently) upon luminosity. Imaging of known $z > 4$ quasars with the Hubble Space Telescope will soon constrain the fraction of gravitationally lensed high-redshift quasars (M. Strauss 2002, private communication). We have roughly estimated the importance of such an effect by randomly reducing by a factor $\approx 2$–$5$ the UV luminosity densities of $\approx 10\%$ (i.e., two to three objects) of the $z > 4$ quasars, including the PSS sample. The partial correlation results from this exercise do not change significantly from the previous analysis; the $\alpha_{\text{ox}}$–$l_{\text{UV}}$ relation is still present.

Finally, we have assessed if our main results above are sensitive to our chosen cosmology by repeating our analyses with a $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.0$ cosmology (see § 1). Our main results appear qualitatively unchanged for this choice of cosmology.

4.5. $l_X$ versus $l_{\text{UV}}$

Previous studies of optically selected quasars have found a strong correlation between optical and X-ray luminosity densities (e.g., Zamorani et al. 1981), parameterized by $l_X \propto l_{\text{UV}}^{\beta}$, with $\beta$ typically varying from $\approx 0.7$ (e.g., Pickering et al. 1994; Wilkes et al. 1994) to $\approx 0.8$ (e.g., Avni & Tananbaum 1986). Most of these studies were based on Einstein data, and the results were obtained using the detection and bounds method described by Avni et al. (1980), i.e., taking into account both detections and upper limits. Using a different approach, stacking analysis, Green et al. (1995) obtained a similar result ($\beta \approx 0.86$) for a sample of Large Bright Quasar Survey (LBQS; Hewett, Foltz, & Chaffee 1995) quasars observed in the RASS. On the other hand, a study by La Franca et al. (1995), based on Einstein data, found that the slope for the ultraviolet–X-ray relationship was consistent with unity using the modified orthogonal distance regression method (Fasano & Vio 1988), which accounts for errors in both variables and intrinsic scatter in the data. However, as pointed out by Yuan et al. (1998a), the significant dispersion in the data and, possibly, their inhomogeneous object selection, could induce a steeper correlation slope.

Finding a nonlinear $l_X$–$l_{\text{UV}}$ correlation (with a slope less than unity) for our SDSS sample of RQQs would support our previous results (see § 4.4) in a totally unbiased way. While a certain degree of anticorrelation is expected between $\alpha_{\text{ox}}$ and $l_{\text{UV}}$ given the presence of the UV luminosity term in the $\alpha_{\text{ox}}$ formula, no correlation is mathematically expected a priori between $l_X$ and $l_{\text{UV}}$. With the present work, we confirm previous results about the existence of a strong correlation between $l_X$ and $l_{\text{UV}}$, with an extension to the highest redshifts/luminosities, given the inclusion of $z > 4$ quasars recently observed by Chandra and XMM-Newton. We used the generalized Kendall $\tau$-statistic (Brown, Hollander, & Korwar 1974) to evaluate the significance of the result and the EM algorithm (Dempster et al. 1977) and the Buckley-James method (Buckley & James 1979) to derive the parameters of the relationship. We find a significant correlation (see Fig. 8), parameterized by

$$l_X \propto l_{\text{UV}}^{0.71 \pm 0.06},$$

including BALQSOs ($7.8 \sigma$ significance level) and

$$l_X \propto l_{\text{UV}}^{0.75 \pm 0.06},$$

excluding BALQSOs ($7.9 \sigma$ significance level). The latter correlation is shown in Figure 8 (dashed line). For comparison purposes, the dotted line shows a correlation with $\beta = 1$ constrained to pass through the mean $l_X$ and $l_{\text{UV}}$.

The inclusion of the PSS quasars at $z > 4$ has the effect of increasing the significance of this correlation up to $9.3 \sigma$ (both with and without the BALQSOs), and the basic parameters of the correlation remain unchanged. The significance of this correlation over a large redshift and luminosity range suggests that it is a universal property of optically selected (and also X-ray-selected; e.g., La Franca et al. 1995) quasars.

We have investigated if $\beta$ has any redshift dependence. Using the RQQs at $z < 1.5$ ($z > 1.5$), we find $\beta = \ldots$ 

![Fig. 8. A plot of $l_X$ vs. $l_{\text{UV}}$. Triangles indicate SDSS RQQs observed in pointed X-ray observations (excluding BALQSOs). The dashed line indicates the best-fit relationship obtained when BALQSOs are excluded from the analysis. For comparison purposes, the dotted line shows a correlation with $\beta = 1$, constrained to pass through the average $l_X$ and $l_{\text{UV}}$.](image-url)
0.61 ± 0.11 (β = 0.90 ± 0.19 excluding BALQSOs and β = 0.79 ± 0.20 including BALQSOs); the division at z = 1.5 has been chosen to give approximately the same number of objects in each redshift interval. Therefore, we do not detect any highly significant variation of β with redshift.

Using the definition of α\text{ox}, the equation α\text{ox} = A l_{\text{UV}} + B l_{\text{X}} (see § 4.4) and l_{\text{X}} \propto l_{\text{UV}}^{\beta}, we can derive A1 as a function of β and some constant terms. Using the range of l_{\text{UV}} for our SDSS sample and the constant terms reported in equations (2) and (4), we derive A1 ≈ −0.10. This is entirely consistent with the value reported in equation (2).

5. DISCUSSION

5.1. Results from the SDSS RQQ Sample

We have presented the X-ray properties of the color-selected SDSS RQQs, mainly taken from the EDR, using ROSAT, Chandra, and XMM-Newton data. In the 0.16–6.28 redshift range, we detect 67/137 SDSS RQQs covered by pointed X-ray observations and an additional 69 SDSS RQQs observed by the RASS. We have used the unbiased sample of 137 RQQs with pointed X-ray observations to investigate the dependence of the α\text{ox} index upon rest-frame 2500 Å luminosity and redshift using partial correlation analysis applied to censored X-ray data. The principal results of our study are the following:

1. The optical–to–X-ray spectral slope, α\text{ox}, is anticorrelated with l_{\text{UV}} at the 3.4–3.7 σ significance level, although the scatter in this anticorrelation is large (see § 4.4). The inclusion of 13 z > 4, high-luminosity, PSS quasars increases slightly the significance of the α\text{ox}–l_{\text{UV}} anticorrelation to 3.8–3.9 σ. There is no significant correlation between α\text{ox} and redshift, even when the sample of PSS quasars is included. These results suggest that the mechanism driving quasar broadband emission (i.e., accretion onto a supermassive black hole) is similar in the local and the early universe. They also indicate that, although it is likely that high-redshift quasars are radiating at higher fractions of their Eddington luminosity (e.g., Kauffmann & Haehnelt 2000), there are no unusual phenomena such as accretion disk instabilities (e.g., Lightman & Eardley 1974; Shakura & Sunyaev 1976) or “trapping radius” effects (e.g., Begelman 1978; Rees 1978) seem to be dominant. It appears that already at z ≈ 6 quasars are almost completely built-up systems, even though the time available was short at those epochs (≲ 1 Gyr in our cosmology).

2. We confirm the l_{\text{X}}–l_{\text{UV}} correlation as being an intrinsic property for optically selected RQQs. This correlation can be parameterized by l_{\text{X}} \propto l_{\text{UV}}^{0.75 ± 0.06}, in good agreement with most previous work.

5.2. Comparison with Earlier Work

The α\text{ox} dependence upon luminosity and redshift has been studied for many years. However, most earlier studies, although generally providing results consistent with ours (i.e., α\text{ox} depends mainly upon l_{\text{UV}}), were limited by heterogeneous selection criteria of the samples (e.g., Avni et al. 1995) or limited coverage in redshift/luminosity. As pointed out by Yuan, Siebert, & Brinkmann (1998b) using Monte Carlo simulations, a spurious anticorrelation between α\text{ox} and UV luminosity density can emerge even for a population with an intrinsically constant α\text{ox}, provided that the dispersion of the UV luminosities is similar to or larger than that of the X-ray luminosities. Analysis of the dispersions of l_{\text{UV}} and l_{\text{X}} for the SDSS RQQs used in this work indicates that the α\text{ox}–l_{\text{UV}} anticorrelation is likely to be real.

The lack of sensitive radio surveys (e.g., FIRST, NVSS, Condon et al. 1998) prevented the early studies of quasars from clearly discriminating between the radio-quiet and radio-loud populations (except for the sources detected at high radio flux densities); these two populations have been known to have different emission properties in the X-ray band since Einstein (e.g., Zamorani et al. 1981; Wilkes & Elvis 1987). In this regard, the sensitive radio coverage for all of the quasars used in our study allowed us to select a sample of “pure” RQQs without contamination by radio-loud objects.

The only results indicating that α\text{ox} depends upon redshift have been presented by Yuan et al. (1998a) and Bechtold et al. (2002). Yuan et al. (1998a), using a large database of RQQs seen in the RASS and ROSAT pointed observations, found that α\text{ox} depends on 2500 Å luminosity at l_{\text{UV}} > 30.5 ergs s^{-1} Hz^{-1} and slightly on redshift at z < 0.5. We did not find the latter dependence, but the number of SDSS RQQs with X-ray coverage at z < 0.5 is small (15 RQQs). Bechtold et al. (2002) reported a significant α\text{ox}–redshift anticorrelation for a large sample of quasars observed by ROSAT (data taken from Yuan et al. 1998a) and Chandra over the same redshift range as our study. The heterogeneous selection and construction criteria of the Bechtold et al. (2002) sample, coupled with the lack of a partial correlation analysis, might lead to different results than ours.

5.3. Future Possibilities and Work

Studies using a larger number of objects and, hopefully, a higher fraction of X-ray detections are required to address all the issues related to α\text{ox} dependences upon luminosity or redshift. A larger number of SDSS quasars will soon become available to the scientific community with the next data release, which will provide a factor of ≳ 5 increase in the number of SDSS optically selected objects. From an X-ray perspective, most of these quasars are likely to be detected easily with snapshot observations by modern X-ray satellites. Furthermore, given the large field of view of the EPIC instruments on board XMM-Newton (≈155′ radius), we expect a sizeable number of serendipitously observed SDSS RQQs in the next few years.

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