THE REDDEST DR3 SDSS/XMM-NEWTON QUASARS

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ABSTRACT

We have cross-correlated the SDSS DR3 Schneider et al. (2005) quasar catalog with the XMM-Newton archive. Color and redshift selections (\(g-r \geq 0.5\) and \(0.9 < z < 2.1\)) result in a sample of 17 red, moderate-redshift quasars. The redshift selection minimizes possible contamination due to host galaxy emission and Ly\(\alpha\) forest absorption. Both optical and X-ray information is required to distinguish between the two likely remaining causes of the red colors: (1) dust reddening and (2) an intrinsically red continuum. We find that 7 of 17 quasars can be classified as probable “intrinsically red” objects. These seven quasars have unusually broad Mg \(\alpha\) emission lines (FWHM = 10,500 km s\(^{-1}\)), moderately flat but unabsorbed X-ray spectra (\(\Gamma = 1.66 \pm 0.08\)), and low accretion rates (\(\dot{M}/\dot{M}_{\text{Edd}} \sim 0.01\)). We suggest low accretion rates as a possible physical explanation for quasars with intrinsically red optical continua. We find that 8 of 17 quasars can be classified as dust reddened. Three of these have upper limits on the absorption column from X-ray spectral fits of #\(N_{\text{H}} = (3-13) \times 10^{22}\) cm\(^{-2}\), while the other five quasars must be absorbed by at least #\(N_{\text{H}} = 10^{23}\) cm\(^{-2}\) in order to be consistent with a comparably selected \(\alpha_{\text{ox}} - I_{\text{uv}}\) distribution. Two objects in the sample are unclassified.

Subject headings: accretion, accretion disks — galaxies: active — quasars: general

1. INTRODUCTION

Until recently, quasars have typically been selected as point-like objects with colors bluer than stars (e.g., \(U-B < -0.48\); Schmidt & Green 1983). This limited the possible spectral energy distributions (SEDs) that known quasars could have. A composite SED shows that quasars’ blue colors are due to the big blue bump (BBB) continuum feature that dominates the optical and UV spectrum (Malkan & Sargent 1982; Elvis et al. 1994). However, surveys using different selection mechanisms discovered that quasars can have red colors as well, indicating a diminished or missing BBB. While in many cases this reddening is due to dust obscuration, some cases may be due to changes in the accretion disk thought to power the optical/UV continuum. We identify such a population in this paper.

Red quasars were first discovered in the Webster et al. (1995) sample of radio-loud quasars. Webster et al. (1995) suggested dust reddening as the cause of the red \(B-K\) colors and estimated that red colors could cause as much as 80% of the quasar population to go undetected in existing optical surveys. Some 200 members of a new population of red, radio-quiet quasars were discovered in the near-infrared (1–2 \(\mu\)m) with the Two Micron All Sky Survey (2MASS) by Cutri et al. (2002). The space density of the red 2MASS quasars was found to be at least equal to that of optical- and UV-selected quasars. Cutri et al. (2002) also suggested dust reddening to explain the colors of the red 2MASS quasars because the near-IR color distribution is consistent with a reddening of \(A_F = 1\)–5 mag. In addition, \(\sim 10\%\) of the predominantly radio-quiet sample is highly polarized (\(P > 3\%\); Smith et al. 2002).

Supporting this conclusion, Chandra and XMM-Newton observations of red 2MASS quasars find spectra that are either unusually hard or absorbed by \(N_{\text{H}} = 10^{21} - 10^{23}\) cm\(^{-2}\) (Wilkes et al. 2002, 2005; Urrutia et al. 2005).

Unlike UV-excess-based surveys, the Sloan Digital Sky Survey (SDSS) allows detection of red quasars in the optical band because the algorithm for selecting candidates for spectroscopy uses a four-dimensional multicolor selection criterion (Richards et al. 2003, hereafter R03) similar to that of the 2dF QSO Redshift Survey (Croom et al. 2004). This allows the SDSS to select all objects lying outside of the stellar locus, including atypically red quasars. R03 explored the color distribution of SDSS quasars and found that while a population of intrinsically red quasars exists, the majority of the red tail of the color distribution is explained by dust reddening. In a later study (Hopkins et al. 2004), the curvatures of the SDSS spectra were found to be best fitted by a dust extinction curve similar to that of the Small Magellanic Cloud (SMC; Prevot et al. 1984). However, only mildly dust-reddened quasars can be detected \([E(B-V) < 0.5]\) in the SDSS before dust extinction causes them to drop below the detection threshold of the survey (R03).

While dust reddening is a common explanation for red colors in quasars, other possible explanations include (1) host galaxy contamination, (2) absorption by the Ly\(\alpha\) forest, (3) optical synchrotron emission superimposed on a normal, blue spectrum to create a red spectrum (Serjeant & Rawlings 1996; Francis et al. 2000; Whiting et al. 2001), and (4) an intrinsically red continuum. The redshift selection in this paper minimizes contamination via options 1 and 2.

X-ray observations used in conjunction with optical information can constrain the amount of intrinsic absorption in a source, thereby allowing an investigation of dust-reddened versus intrinsically red optical continua. Previous studies have found intrinsically red quasar candidates in addition to dust-reddened quasars. For example, Hall et al. (2006) selected a sample of 12 red quasars from the SDSS, but Chandra X-ray observations show evidence for absorption \([N_{\text{H}} \sim 10^{22}\) cm\(^{-2}\]) in only 4 of their 12 quasars. The other 8 quasars show no evidence for even moderate intrinsic absorption, and 3 of these show evidence for an intrinsically red optical continuum.

In a similar vein, Risaliti et al. (2003) observed 16 optically selected, X-ray-weak quasars with Chandra. While the sample was not selected to be red, the average color of the sample is redder than that of the parent Hamburg Quasar Survey \([\Delta(B-R) \sim 1\) vs. \(\Delta(B-R) \sim 0.5]\). The X-ray-weak quasars have a flat average photon index, \(\Gamma = 1.5\) (where \(\Gamma = -\alpha + 1\) for \(F_{\nu} \propto \nu^{\alpha}\)), and 12 of the 16 quasars have steeper optical–to–X-ray indices than

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normal. The optical–to–X-ray continuum is characterized by \( \alpha_{\text{ox}} = \frac{\log (F_{2\text{keV}}/F_{\text{uv}})}{\log (\nu_{2\text{keV}}/\nu_{\text{uv}})} \), where \( F_{2\text{keV}} \) and \( F_{\text{uv}} \) are the intrinsic flux densities at 2 keV and 2500 Å, respectively (Tananbaum et al. 1979). While X-ray absorption remains a possibility, Risaliti et al. (2003) argue that these quasars are intrinsically underluminous in the X-rays. The evidence, however, is not conclusive due to the low signal-to-noise ratio (S/N) for many of the Chandra spectra.

Larger surveys including high-quality optical and X-ray spectra are now possible with the advent of the SDSS and the XMM-Newton archive of X-ray observations, both of which cover large areas of the sky. SDSS data can constrain dust reddening in the optical, while XMM-Newton observations constrain absorption in the X-rays. In this paper we investigate the optical and X-ray properties of 17 red SDSS quasars. Section 2 introduces the data sources and sample selection, and § 3 covers the optical and X-ray reduction and data analysis. In § 4 we classify the quasars as dust reddened, intrinsically red, or unclassified, and in § 5 we discuss low accretion rates as a possible explanation for the steep optical/UV spectra of intrinsically red quasars. We assume throughout the paper that \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_M = 0.3 \), and \( \Omega_{\Lambda} = 0.7 \).

2. SAMPLE SELECTION

2.1. Data Sources: SDSS and XMM-Newton

The third version of the SDSS quasar catalog (Schneider et al. 2005) is based on Data Release 3 (DR3), which covers an area of 5282 deg\(^2\) (Abazajian et al. 2005). The quasar catalog contains 46,240 objects from the SDSS that have (1) \( 15.0 < i < 22.2 \), (2) \( M_i < -22.0 \), (3) at least one emission line with FWHM greater than 1000 km s\(^{-1}\), or (4) unambiguous broad absorption line (BAL) characteristics. SDSS photometry in the \( u, g, r, i, \) and \( z \) bands covers 3250–10000 Å. SDSS spectroscopy covers 3800–9200 Å (so the \( u \) band and part of the \( z \) band lie outside the spectral range), with a spectral resolving power of \( \approx 2000 \).

The SDSS DR3 quasar catalog overlaps with 1% of the area of archival XMM-Newton observations. XMM-Newton imaging is carried out by three European Photon Imaging Cameras (EPIC): MOS-1, MOS-2, and pn (Turner et al. 2001; Struder et al. 2001). The XMM-Newton telescope is good for retrieving serendipitous X-ray spectra of SDSS quasars due to a large collecting area (922 cm\(^2\) for MOS and 1227 cm\(^2\) for pn at 1 keV), large field of view (33′×33′ for MOS and 27.5′×27.5′ for pn), and good spectral resolution (\( E/\Delta E \approx 20–50 \) for both MOS and pn). The XMM-Newton spectral range covers the 0.5–12 keV band.

The SDSS and XMM-Newton archives are well matched in sensitivity. A source with a 2–10 keV flux of \( 10^{-14} \text{ ergs s}^{-1} \text{ cm}^{-2} \) and a standard radio-quiet spectrum (\( T \sim 2.0 \)) produces \( \sim 100 \) counts in \( \sim 10 \) ks, sufficient for a crude spectral fit. For a typical value of \( \alpha_{\text{ox}} \approx -1.5 \) (Vignali et al. 2003), a \( 10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1} \) quasar would have \( r = 19.37 \) while an X-ray-quiet quasar with \( \alpha_{\text{ox}} = -2.0 \) would have \( r = 15.63 \). Both of these magnitudes lie comfortably in the SDSS range.

2.2. The SDSS-XMM Red Quasar Sample

We define our red sample of Schneider et al. (2005) quasars lying in XMM-Newton fields by selecting the most extreme red colors, \( g - r \geq 0.5 \). By further restricting our search to moderate redshifts \( (0.9 < z < 2.1) \), we minimize host galaxy contribution at low redshifts \( (z < 0.5) \) and Ly\( \alpha \) forest absorption at high redshifts \( (z > 2.5) \). This selection results in a sample of 17 quasars.

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4 See http://imagine.gsfc.nasa.gov/docs/sats-n_data/missions/xmm.html.

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R03 defines dust-reddened quasars via their relative colors. Relative colors compare a quasar’s measured colors with the median colors in its redshift bin, where redshift bin sizes are 0.1 in redshift, so that \( \Delta(g - i) = (g - i) - ((g - i)_{\text{median}}) \). The use of relative colors corrects for the effect of typical emission lines on the photometry in a particular band. The relative colors of the SDSS quasars match a Gaussian distribution on the blue side but require the addition of a tail on the red side (Fig. 3 in R03). R03 identifies quasars belonging to the red tail as \( \Delta(g - i) > 0.2 \), since the \( \Delta(g - i) \) color correlates best with the photometric spectral index. The \( \Delta(g - i) \) color has been corrected for an SMC-like extinction curve with \( E(B - V) = 0.04 \), a value typical of high Galactic latitudes, for which \( E(g - i) = 0.07 \). In practice, this yields a minimum of \( \Delta(g - i) \approx 0.35 \) for the quasars with redshift \( z \approx 1.5 \). The \( (g - i) \) and \( (g - r) \) colors behave similarly with redshift (Fig. 2 of R03), and the maximum median color is 0.2 for \( 1 < z < 2 \). In Figure 1 we show a histogram of the relative \( (g - i) \) colors for our sample. Only two have \( \Delta(g - i) < 0.35 \). Thus, the \( g - r \geq 0.5 \) color selection mimics \( \Delta(g - i) > 0.35 \), although we do not use relative colors.

Our red quasar sample is unbiased in X-ray loudness since we do not require X-ray detections for selection. Nevertheless, the X-ray detection rates are high: 94% for 2 \( \sigma \) detections (16/17) and 76% for >3 \( \sigma \) detections (13/17), although most of the quasars have a relatively low X-ray S/N: 10/17 quasars have S/N < 10.

Table 1 lists the sample, giving the source ID number used within this paper, the full SDSS name, radio classification, X-ray S/N (which is averaged if multiple observations are available), redshift, Galactic \( N_{\text{HI}} \), and the absolute \( i \)-band magnitude \( M_i \). A source is radio-loud if \( F_{5\text{GHz}}/F_{4800} = R_L \geq 10 \) (Kellerman et al. 1989). To calculate \( R_L \), a power law is interpolated between the optical magnitudes to get \( F_{5\text{GHz}} \), and the 1.4 GHz radio flux is obtained from FIRST survey detections (White et al. 1997), which are extrapolated to 5 GHz using a radio power law \( \alpha_{R} = -0.8 \). All the quasars lie in the area covered by the FIRST survey, so if there is no detection, we use the 5 \( \sigma \) upper limit on the 1.4 GHz radio flux to extrapolate to 5 GHz.

For 5 of 17 sources, there are two X-ray observations. In these cases, both observations were processed and used in our analysis.
TABLE 1

| Source ID | SDSS Name     | $R_L$  | (S/N)$_g$ | $z$ | $N_{H,gal}$ (10$^{20}$ cm$^{-2}$) | $M_2$ |
|-----------|---------------|--------|-----------|-----|---------------------------------|-------|
| 1         | SDSS J0944+0410 | 0.50   | 1.58      | 1.98 | 3.63                            | -25.3 |
| 2         | SDSS J0327-0731 | 0.53   | 1.25      | 1.92 | 3.05                            | -23.6 |
| 3         | SDSS J1652+3947 | 0.54   | 1.65      | 1.90 | 2.59                            | -24.2 |
| 4         | SDSS J0200+0203 | 0.55   | 1.58      | 1.94 | 2.07                            | -24.7 |
| 5         | SDSS J0958+0130 | 0.52   | 1.25      | 1.92 | 3.05                            | -23.6 |
| 6         | SDSS J1533+2243 | 0.54   | 1.65      | 1.90 | 2.59                            | -24.2 |
| 7         | SDSS J1652+3947 | 0.54   | 1.65      | 1.90 | 2.59                            | -24.2 |
| 8         | SDSS J0951+4851 | 0.51   | 1.23      | 1.92 | 3.05                            | -23.6 |
| 9         | SDSS J0958+0130 | 0.52   | 1.25      | 1.92 | 3.05                            | -23.6 |

a The radio-loud parameter $R_L$ is defined as $F_{4000}$/F$_{5000}$, where $R_L > 10$ indicates radio loudness (Kellerman et al. 1989).

b When more than one X-ray observation exists for a single source, the S/N listed is the rms of the observations.

TABLE 2

| ID | SDSS Name     | $g - r$ | $i$ | Mg ii FWHM (km s$^{-1}$) |
|----|---------------|---------|-----|--------------------------|
| 1  | SDSS J0944+0410 | 0.50    | 18.22 | 8800                     |
| 2  | SDSS J0327-0731 | 0.53    | 19.25 | 11700                    |
| 3  | SDSS J1652+3947 | 0.54    | 18.65 | 8800                     |
| 4  | SDSS J0200+0203 | 0.55    | 18.58 | 10800                    |
| 5  | SDSS J0958+0130 | 0.52    | 18.10 | 7700                     |
| 6  | SDSS J1533+2243 | 0.97    | 18.69 | 6700                     |
| 7  | SDSS J1114+5315 | 0.59    | 18.01 | 7700                     |
| 8  | SDSS J1133+4900 | 0.50    | 18.78 | 7000                     |
| 9  | SDSS J1227+0812 | 0.62    | 19.06 | 5800                     |
| 10 | SDSS J1114+5315 | 0.76    | 18.77 | 6400                     |
| 11 | SDSS J1133+4900 | 0.52    | 18.42 | 9100                     |
| 12 | SDSS J1227+0812 | 0.62    | 19.06 | 5800                     |
| 13 | SDSS J1227+0812 | 0.59    | 19.66 | 10500                    |
| 14 | SDSS J0959+0209 | 0.60    | 19.40 | 23200                    |
| 15 | SDSS J1053+5735 | 0.55    | 18.95 | 5400                     |
| 16 | SDSS J0913+5259 | 0.64    | 16.20 | 6000                     |

2.3. SDSS Data

SDSS photometry was extracted from the online database via SQL-based queries in CasJobs. The individual, calibrated SDSS spectra were also downloaded from the SDSS database. Table 2 gives the source ID, the abbreviated SDSS name, the $g - r$ color (which determined selection), the apparent $i$-band magnitude, and the full width at half-maximum (FWHM [km s$^{-1}$]) of the broad Mg ii component. The Mg ii information is taken from Shen et al. (2008) for all but three objects. Shen et al. (2008) simultaneously fit the Fe ii emission, a continuum power law, and broad and narrow Gaussians to the Mg ii line. The spectral S/N is too low for two objects (sources 13 and 15) to use this method. Another object (source 17) has good S/N, but line values are not given in Shen et al. (2008). We fit the Mg ii lines for these three sources by estimating the continuum values by eye and then simultaneously fitting broad and narrow Gaussians with IRAF.

There is one BAL quasar in the sample, SDSS J0944+0410 (source 1), and two narrow absorption line (NAL) quasars, SDSS J1226+0130 (source 8) and SDSS J1435+4851 (source 9). Only 5 of the 17 quasars have the C iv line, which is the most reliable marker of BAL/NAL presence, visible in their spectra. Mg ii, the broad emission line seen in all 17 quasars, rarely shows either BALs or NALs. So the true number of BALs and NALs in the sample could be even greater.

2.4. X-Ray Data Reduction

Using the XMM-Newton Science Analysis System, SAS v7.02, we filtered the XMM-Newton observations to remove time intervals of flaring high-energy background events using the standard cutoff of 0.35 counts s$^{-1}$ for the MOS cameras and 1.0 count s$^{-1}$ for the pn camera. The event rate plots were visually examined to determine that these cutoffs were appropriate. We then extracted source and background regions for spectral analysis. The SAS task eregionanalyse was used to select the source radius with the optimal S/N, with typical radii ranging from 10$^0$ to 60$^0$. Background regions were defined by eye, avoiding obvious X-ray sources and chip edges. These regions were typically a circle of radius 2000–2500 pixels (100$''$–250$''$), selected to lie on the same chip as the source and as close to the source as possible without overlapping the source extraction region.

Where possible, observations were retrieved for all three XMM-Newton EPIC CCDs. In seven observations, the source lies in a bad region in one of the cameras, either in a strip between two chips or, because the MOS and pn cameras have different shapes,

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Note:—FWHM measurements for the Mg ii broad emission lines are from Shen et al. (2008).

The line parameters for these sources are not included in Shen et al. (2008). Instead, broad and narrow Gaussians were fitted simultaneously to the line, with the continuum estimated by eye. The FWHMs for the broad Gaussian component are listed.
the source may lie outside the field of view in one of the cameras. In an eighth case, the source is within the field of view of all three cameras, but in the MOS-2 camera, most of the events are filtered out while removing the flaring high-energy background. In all of these cases (7 of 22 observations), we use the remaining images from the other cameras for analysis.

Table 3 contains data for the XMM-Newton observations, ordered by increasing S/N. The table includes the source ID, XMM-Newton identification number, observation date, net exposure time, net counts, X-ray S/N, and the cameras available for analysis.

| Source ID | XMM ID | Date       | Net Exposure Timea (ks) | Net Countsa (counts) | S/N    | Cameras |
|-----------|--------|------------|-------------------------|----------------------|--------|---------|
| 1…………..| 0201290301 | 2005 Jun 9  | 56.7                    | 0.03                 | 0.2    | …X X   |
| 2…………..| 0200730401 | 2005 Jan 30 | 122.8                   | 40.3                 | 3.2    | X X X  |
| 3a…………..| 0113060401 | 2002 Jul 14 | 4.55                    | 7.3                  | 1.2    | …X X   |
| 3b…………..| 0113060201 | 2003 Sep 3  | 5.0                     | 19.2                 | 2.6    | …X X   |
| 4………….. | 0145450501 | 2003 Dec 4  | 9.2                     | 25.1                 | 2.9    | X X X  |
| 5a…………..| 0203360401 | 2005 Dec 10 | 29.6                    | 39.0                 | 2.8    | X X X  |
| 5b…………..| 0203360801 | 2005 Dec 7  | 89.4                    | 11.8                 | 2.9    | X X X  |
| 6………….. | 0009650201 | 2002 Sep 20 | 40.2                    | 31.2                 | 2.9    | …X X   |
| 7………….. | 0039140101 | 2003 Aug 29 | 25.3                    | 70.8                 | 4.0    | X X X  |
| 8………….. | 0110990201 | 2002 Aug 11 | 32.3                    | 70.3                 | 4.7    | X X X  |
| 9………….. | 0110930401 | 2004 Feb 4  | 21.1                    | 77.5                 | 4.2    | X X X  |
| 9b…………..| 0110930901 | 2004 Feb 4  | 17.7                    | 98.3                 | 4.7    | X X X  |
| 10………….| 0009650201 | 2002 Sep 20 | 40.2                    | 84.5                 | 5.9    | …X X   |
| 11………….| 0143650901 | 2004 May 20 | 17.1                    | 135.3                | 6.3    | X X X  |
| 12………….| 0149900201 | 2004 Dec 15 | 36.0                    | 196.3                | 8.7    | …X X   |
| 13………….| 0081340201 | 2002 Nov 2  | 60.1                    | 750.0                | 14.4   | X X X  |
| 14………….| 0203361801 | 2005 Jan 16 | 79.3                    | 1486.8               | 21.9   | X X X  |
| 15………….| 0203361801 | 2005 Jan 16 | 79.9                    | 2696.2               | 27.9   | X X X  |
| 16………….| 0147511701 | 2004 Feb 1  | 282.4                   | 4185.3               | 33.7   | X X X  |
| 16b………….| 0147511801 | 2004 Feb 17 | 4775.3                 | 36.8                | X X X  |
| 17a………….| 0143150301 | 2004 Sep 6  | 20.8                    | 3867.3               | 33.6   | X X X  |
| 17b………….| 0143150601 | 2004 Sep 6  | 47.9                    | 9130.1               | 53.4   | X X X  |

* Net exposure time and net counts include information from all available observations. Net counts are taken from 0.5 to 10 keV.

3. ANALYSIS

3.1. Optical Spectra and Continuum Dust Reddening Fits

We wrote an IDL procedure to fit dust reddening to the optical continuum. The procedure calls a dereddening routine, FM_UNRED.PRO, which uses the Fitzpatrick (1999) parameterization to characterize the optical and UV extinction curve.

Each source spectrum is first shifted to the rest frame. A composite quasar spectrum created from SDSS quasars (Vanden Berk et al. 2001) is then reddened incrementally with the SMC extinction curve (Gordon et al. 2003) and normalized to the red quasar spectrum by averaging the continuum between 3200 and 3066 Å (Vanden Berk et al. 2001) in order to calculate the \( \chi^2 \) value. The best-fit parameters are those for which \( \chi^2 \) reached a minimum. The total \( \chi^2 \) was allowed to vary by 2.7 to get the 90% confidence interval errors.

The SMC, rather than Galactic, extinction curve is used because of the absence of the \( \lambda 2175 \) feature in AGN spectra (Pitman et al. 2000; Kuhn et al. 2001; Czerny et al. 2004; Hopkins et al. 2004). The optical dust reddening [hereafter denoted as \( E(B-V)_{\text{spec}} \)] is allowed to vary from \( E(B-V)_{\text{spec}} = 0.0 \) to 1.0. Simulations have shown that quasars with \( E(B-V) > 0.5 \) are not expected from the SDSS selection process (R03), so the fits to the spectral continuum cover the full \( E(B-V) \) parameter space.

The small blue bump, a blend of Balmer continuum emission and Fe\( \text{II} \) lines, extends from \( \sim 2000 \) to \( 4000 \) Å (Wills et al. 1985). Our color selection criteria (\( g - r \geq 0.5 \)) bias our sample toward sources with atypically large Fe\( \text{II} \) emission between \( \sim 2200 \) and \( 2700 \) Å. Five of 17 sources have atypical Fe\( \text{II} \) emission. Excluding the region from 2200 to 3000 Å from the \( \chi^2 \) calculation for all the sources accounts for both Fe\( \text{II} \) emission and the Mg\( \text{II} \) \( \lambda 2798 \) line, so that the reddening fit to the continuum is not biased by unusually strong line emission. The reddening fit was not sensitive to other broad emission lines, such as the \( \text{C IV} \ \lambda 1549 \) line, so we did not omit any additional lines from the fit. The BAL quasar (SDSS J0944+0410, source 1) was not fitted with reddening because numerous absorption lines and a strong Fe\( \text{II} \) bump left no reliable continuum points with which to calculate \( \chi^2 \).

We also fit a power law (\( F_{\nu} \propto \nu^{\alpha_{\text{opt}}} \)) to the optical continuum. All major emission lines are removed before performing the fit, as is the region dominated by the blended Fe\( \text{II} \) and Balmer emission. A power law will not be a good fit to spectral continua with obvious dust curvature, but for \( E(B-V)_{\text{spec}} < 0.1 \), dust reddening will look similar to a red power law. Section 3.2 discusses this issue in more detail.

Figure 2 plots the SDSS source spectra in \( F_{\nu} (10^{-17} \text{ergs cm}^{-2} \text{s}^{-1} \text{Å}^{-1}) \) versus \( \lambda (\text{Å}) \) space. Overplotted are the original Vanden Berk et al. (2001) template (dotted blue line), the reddened template (dashed red line), and the optical power law (solid green line). Table 4 gives the reddening results: \( E(B-V)_{\text{spec}} \), the expected intrinsic gas column density (\( N_{\text{H opt}} \)) obtained by applying the Galactic gas-to-dust ratio (Bohlin et al. 1978; Kent et al. 1991), the intrinsic gas column density from the X-ray fits (\( N_{\text{H X}} \); see § 3.3), and the optical power-law index, \( \alpha_{\text{opt}} \).

Reddening fits to the optical spectra require \( E(B-V)_{\text{spec}} \) in 14 out of 17 sources at \( > 3 \sigma \). For these 14 sources, \( E(B-V)_{\text{spec}} \) ranges from 0.04 to 0.25, with a weighted mean of \( \langle E(B-V)_{\text{spec}} \rangle = 0.1 \) corresponding to \( \langle N_{\text{H opt}} \rangle = 5.8 \times 10^{20} \text{ cm}^{-2} \), using the Galactic gas-to-dust ratio.
3.2. Testing the Optical Continuum for Weak Curvature with Relative Colors

We find that reddening is a good fit to most of the optical spectra. However, for the redshifts of this sample (z > 1), the optical continuum will not have strong dust-induced curvature for mild reddening $[E(B-V)_{\text{spec}} \leq 0.1]$. Under these conditions, a dust-reddened optical continuum will look similar to a red power law. Figure 2 shows the similarity between mild dust reddening (dashed red line) and a red power law (solid green line). The curvature in the relative broadband photometry can help differentiate these two possibilities because the $u$ band (for which the FWHM ranges from 3251 to 3851 Å) is mostly outside the spectral range (3800–9200 Å). The $u$ band is a factor of 3.6 more absorbed by dust [for $E(B-V) = 0.1$] than the $r$ band, where the spectra are centered.

Relative colors give an idea of the shape of the continuum (Hall et al. 2006). A quasar with a typical $g-i$ color, for example, will have $\Delta(g-i) = 0$, while a quasar with red $(g-i)$ color will have $\Delta(g-i) > 0$. A dust-reddened quasar with typical emission lines will have $\Delta(u-r) > \Delta(g-i) > \Delta(r-z)$ because curvature increases on the blue side of the continuum. A typical blue power-law continuum, on the other hand, will have $\Delta(u-r) \sim \Delta(g-i) \sim \Delta(r-z)$. In the case of a power-law continuum that is redder than average, the relative colors will go as $\Delta(u-r) < \Delta(g-i) > \Delta(r-z)$. Therefore, an object with $\Delta(u-r) - \Delta(g-i) < 0$ displays dust-reddened curvature, while an object with $\Delta(u-r) - \Delta(g-i) > 0$ displays a red power law. We use this criterion to classify quasars as intrinsically red (see § 4.2).

Since relative colors compare the observed quasar colors to the mean colors for quasars at that redshift, atypical emission lines will affect the relative color results. For the redshift range 1 < z < 2, the most significant lines are Mg $\upmu$ and the Fe $\upmu$ emission line blend. To correct for atypical Mg $\upmu$ lines, we calculate the equivalent width of Mg $\upmu$ from the spectrum. From this, we subtract the average Mg $\upmu$ equivalent width obtained from the Vanden Berk composite spectrum (Vanden Berk et al. 2001). The residual Mg $\upmu$ line flux is calculated and added or subtracted from the band where Mg $\upmu$ is found. To correct for the Fe $\upmu$ emission line blend, we redden the composite spectrum, shift it to the observed frame, and normalize to the source spectrum. We then subtract this spectrum from the source for the range 2200–2700 Å and calculate the equivalent width of the residual Fe $\upmu$ line. We add or subtract the residual flux from the bands where Fe $\upmu$ is found. Since the $u$ band is outside of the spectral range, we cannot correct for atypical emission lines in this band. The relative colors and the optical continuum shapes are listed in Table 5.

Fig. 2.—SDSS source spectra plotted as solid black lines, $F_v (10^{-17}$ ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$) vs. $\lambda$ (Å). The original Vanden Berk et al. (2001) template (dotted blue line) and the reddened template (dashed red line) are overplotted. Note that the BAL quasar (SDSS J0944+0410, source 1) had no reliable continuum to fit reddening and so only the original template is plotted. The solid line beneath the spectrum marks the Fe $\upmu$+Mg $\upmu$ region ignored by the continuum-fitting program as described in the text. A power-law fit to the spectrum, with major emission lines omitted, is also shown (solid green line).
3.3. X-Ray Spectral Fits

We made fits to the extracted spectra using the Sherpa package within CIAO. For each source, the available MOS+pn spectra were fitted simultaneously by linking parameters. We used a conservative spectral range of 0.5–10 keV for fitting. The observations were fitted according to their S/N, with more complicated models (models A–E) being applied as S/N increased. Table 6 summarizes the model characteristics. All models applied in this paper include local absorption fixed to the Galactic hydrogen column density ($N_{\text{H, gal}}$) for a source’s coordinates. Values for $N_{\text{H, gal}}$ were taken from WebPIMMS.

For six observations with S/N < 4, we fit model A, where we freeze the photon index of the X-ray power law to $\Gamma = 1.9$. We leave normalization free to vary in order to get the flux or a 90% upper limit on the flux. For five observations with 2 < S/N < 4, we fit model B, a single power law with free $\Gamma$ and normalization. Models A and B use the Cash statistic for fitting, which we discuss further below.

For 14 observations with S/N > 4, we fit model C, a single power law, but using $\chi^2$ statistics rather than Cash. For the same observations, we also fit the spectra with model D, a power law with intrinsic absorption. Finally, for five observations with S/N > 25, we fit model E, a power law with intrinsic absorption, plus a Gaussian for the Fe Kα line. The Gaussian line energy is set to 6.4 keV shifted to the quasar’s reference frame. For sources with S/N > 4 (where models C, D, and E are applied), the $\chi^2$ statistic is used and the data are binned by at least 15 counts bin$^{-1}$.

For S/N < 4, $\chi^2$ is not an appropriate statistic because there are not enough counts per bin, so both models A and B are fitted using the more time-consuming Cash statistic (Cash 1979), which gives more reliable results for low-count sources (Nousek & Shue 1989). When using Cash statistics, the source and background counts are binned by 1 count bin$^{-1}$, to ensure that there are no empty bins. The background is not subtracted and is instead fitted simultaneously with the source. The XMM-Newton background is fitted with the three components described in the XMM-Newton User’s Handbook: a power law fixed to $\Gamma = 1.4$ plus Galactic absorption (to account for the extragalactic X-ray spectrum), a broken power law, with the break energy fixed to 3.2 keV (to account for the quiescent soft proton spectrum), and lines at 1.5 keV for the MOS cameras and at 1.5 and 8 keV for the pn camera (to account for cosmic-ray interactions with the detector). Since this background model has five free parameters for each camera, constraining all fit parameters results in large errors in the best-fit parameters.

Table 7 lists the source ID, the model used for each source, XMM-Newton observation ID, the best-fit spectral slopes, flux values in the ranges 0.5–2 keV and 2–10 keV, luminosity, and the $\chi^2$ or likelihood-of-fit values and degrees of freedom for the best fit. For sources with S/N < 4, Table 7 lists the best-fit parameters for model A, where the spectral slope is fixed to 1.9, leaving the normalization free to vary. (For sources

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8 See http://cxc.harvard.edu/sherpa/threads/index.html.
9 See http://cxc.harvard.edu/ciao/.
10 See http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html.
11 See http://xmm.vilspa.esa.es/external/xmm_user_support/documentation.
with S/N < 2, the best-fit upper limits are listed.) We list the best-fit spectral slopes from model B in Table 8 for reference, but due to the large spectral slope errors, we do not use these values for further analysis.

For sources with S/N > 4, we determine the best-fit model via the F-test, which measures the significance of the change in $\chi^2$ as components are added to a model. In all cases, the more complex models did not have a significantly lower $\chi^2$ value, so for S/N > 4, Table 7 lists the parameters for the power-law model (model C).

Tables 8 and 9 list the best-fit spectral slope and the upper limits on other spectral parameters for rejected models B and D (Table 8) and E (Table 9). Figure 3 shows the data, fits, residuals, and 1, 2, and 3 $\sigma$ $N_H$ contours for the sources with S/N > 4 fitted with model D (power law plus intrinsic absorption).

### 3.4. X-Ray Absorption

Of the 11 sources (and 14 observations) with S/N > 4, none show significant intrinsic absorption, and the F-test demonstrates that all sources prefer a simple power-law model. $N_H$ upper limits (model D) for the five highest S/N sources range from $3 \times 10^{20}$ to $2 \times 10^{21}$ cm$^{-2}$ at the 90% confidence level.

Absorption can also be indicated when the best-fitting power law is unusually hard. Mateos et al. (2005) find an average X-ray photon index $\langle \Gamma \rangle \sim 1.96$ and intrinsic dispersion $\sigma_\Gamma = 0.4$ for a

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**Table 4: Optical reddening fits**

| ID  | $E(B-V)_{spec}$ | $N_H$| $N_LX$| $\alpha_{opt}$ |
|-----|-----------------|-----|-------|--------------|
|     |                 | (10$^{20}$ cm$^{-2}$) | (10$^{20}$ cm$^{-2}$) |             |
| 1   | ...             | ... | ...   | -1.49        |
| 2   | 0.03±0.02       | 1.7±1.2 | ...   | -0.92   |
| 3   | 0.08±0.02       | 4.6±1.2 | ...   | -1.05   |
| 4   | 0.25±0.02       | 14.5±1.2 | ...   | -2.92   |
| 5   | 0.052±0.005     | 3.0±0.3 | ...   | -1.36   |
| 6   | 0.17±0.02       | 9.9±1.2 | ...   | -1.95   |
| 7   | 0.12±0.02       | 7.0±1.2 | ≤696   | -1.85   |
| 8   | 0.15±0.01       | 8.7±0.6 | ≤1340  | -1.79   |
| 9   | 0.13±0.01       | 7.5±0.6 | ≤677   | -2.07   |
| 10  | 0.11±0.02       | 6.4±1.2 | ≤184   | -1.68   |
| 11  | 0.18±0.03       | 10.4±1.7 | ≤89.0  | -1.46   |
| 12  | 0.04±0.01       | 2.3±0.6 | ≤76.3  | -0.87   |
| 13  | 0.09±0.01       | 5.8±4.4 | ≤23.1  | -1.44   |
| 14  | 0.12±0.03       | 7.0±1.7 | ≤54.9  | -1.05   |
| 15  | 0.16±0.05       | 9.3±2.1 | ≤53.9  | -1.94   |
| 16  | 0.11±0.02       | 6.4±1.2 | ≤4.7   | -1.17   |
| 17  | 0.086±0.004     | 5.0±1.7 | ≤2.9   | -1.31   |

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*Gas column predicted from $E(B-V)_{spec}$ using the Galactic gas-to-dust ratio (Bohlin et al. 1978; Kent et al. 1991).

*Gas column upper limit measured via X-ray spectral fits (model D).

*The optical slope as fitted to the spectral continuum with emission lines removed.

The BAL quasar was not fitted with $E(B-V)_{spec}$ because numerous absorption lines made it impractical to fit using $\chi^2$ minimization.

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12 See http://cxc.harvard.edu/ciao3.4/ahelp/ftest.html.
sample of 1137 AGNs found in XMM-Newton fields, with fluxes ranging from $10^{-15}$ to $10^{-12}$ ergs cm$^{-2}$ s$^{-1}$. Mateos et al. (2005) find a systematic hardening of the average X-ray spectra toward fainter fluxes, which they interpret as a higher degree of photoelectric absorption among fainter AGNs. Therefore, we define an unusually hard spectrum to have $\Gamma < 1.5$ at 90% confidence. Two of 14 sources with S/N $> 4$ have unusually hard spectral slopes by this measure: SDSS J1226+0130 (source 8) and SDSS J1435+4841 (source 9). All of the quasars with high enough S/N to fit $\Gamma$ have best-fit spectral slopes flatter than the Mateos et al. (2005) average.

For the five sources with $2 < S/N < 4$ (fitted with model A), the S/N is not high enough to fit a power law or intrinsic absorption. One indicator of X-ray absorption for these sources is X-ray weakness relative to the optical luminosity, defined as $\alpha_{\text{ox}} < -1.8$, where $\alpha_{\text{ox}}$ is the spectral index from 2500 Å to 2 keV. Such small values of $\alpha_{\text{ox}}$ are a common characteristic of BAL quasars, which are known to be heavily absorbed objects in the X-rays (Mathur et al. 1995; Green & Mathur 1996).

To calculate $\alpha_{\text{ox}}$ for the red sample, we use the 2 keV flux ($F_{2\text{ keV}}$) given by the X-ray fits, and we derive the 2500 Å flux ($F_{2500}$) by interpolating a power law between the nearest two of the $ugriz$ magnitudes. We then calculate $\alpha_{\text{ox,corr}}$ by correcting $\alpha_{\text{ox}}$ for absorption. We deredden $F_{\text{ox}}$ using $E(B-V)_{\text{spec}}$ and the Prevot et al. (1984) SMC extinction curve, where $A_{\lambda} = (B-V)_{\text{spec}} 1.39 \lambda^{-1.2}$. For objects with X-ray S/N $> 4$, we do not find significant intrinsic absorption, so we use the 90% upper limit on $N_{\text{H}}$ to correct $F_{2\text{ keV}}$. For objects with X-ray S/N $< 4$, we cannot fit intrinsic absorption, so we make no correction to $F_{2\text{ keV}}$. Table 10 gives the measured and corrected $F_{\text{ox}}$ and $F_{2\text{ keV}}$, $\alpha_{\text{ox}}$ (uncorrected), and $\alpha_{\text{ox,corr}}$ (corrected for absorption).

Figure 4 plots $\alpha_{\text{ox}}$ against the log of the 2500 Å luminosity ($L_{\text{2500}}$) for the red sample. The open circles give the measured $\alpha_{\text{ox}}$ and $L_{\text{2500}}$ values for the red sample. The filled circles give $\alpha_{\text{ox,corr}}$ and $L_{\text{2500,corr}}$, the 2500 Å luminosity corrected for absorption. Solid lines connect the uncorrected values to the corrected values for each source. The five sources with X-ray S/N $< 4$ are marked in red. The Strateva et al. (2005, hereafter S05) sample and $\alpha_{\text{ox}}|_{L_{\text{2500}}}$ correlation are plotted as black points and a solid line, respectively, for comparison. The dotted line marks $\alpha_{\text{ox}} = -1.8$; those sources with $\alpha_{\text{ox}} < -1.8$ are X-ray weak relative to the optical luminosity. All five sources with $2 < S/N < 4$ are X-ray weak, possibly because we were unable to correct the X-ray flux for absorption. All 11 sources with S/N $> 4$ are X-ray normal once corrected for absorption ($\alpha_{\text{ox,corr}} > -1.8$).

Correction for absorption can have a large effect on $F_{2\text{ keV}}$, which can in turn have a large effect on $\alpha_{\text{ox}}$. The largest correction in our sample, for an $N_{\text{H}}$ upper limit of $10^{23}$ cm$^{-2}$, led to a factor of 9.5 change in $F_{2\text{ keV}}$. An additional correction for dust reddening changed $F_{\text{2500}}$ by a factor of 3, leading to $\Delta(\alpha_{\text{ox}}) = 0.2$. Sources with low S/N and/or high $N_{\text{H}}$ upper limits will have a large but undetermined uncertainty in $\alpha_{\text{ox}}$, which makes it difficult to tell if the source is intrinsically weak relative to the optical, or if the X-ray weakness is due only to absorption.

### Table 5

| ID | $\Delta(u - r)$ | $\Delta(g - i)$ | $\Delta(r - z)$ | Continuum Shape |
|----|----------------|----------------|----------------|----------------|
| 1  | 0.97±0.06      | 0.68±0.06      | 0.13±0.04      | Dust           |
| 2  | 0.96±0.07      | 0.25±0.04      | 0.03±0.07      | Dust           |
| 3  | 0.79±0.04      | 0.41±0.03      | 0.29±0.04      | Dust           |
| 4  | 1.26±0.08      | 0.81±0.03      | 0.65±0.04      | Dust           |
| 5  | 0.63±0.04      | 0.71±0.04      | 0.16±0.04      | Red power law ($\alpha_{\text{opt}} = -1.36$) |
| 6  | 1.06±0.07      | 0.83±0.03      | 0.52±0.05      | Dust           |
| 7  | 1.10±0.06      | 0.69±0.02      | 0.23±0.04      | Dust           |
| 8  | 1.13±0.06      | 0.74±0.04      | 0.58±0.04      | Dust           |
| 9  | 0.99±0.07      | 0.77±0.03      | 0.56±0.04      | Dust           |
| 10 | 0.77±0.07      | 0.74±0.03      | 0.41±0.06      | Undefined      |
| 11 | 0.80±0.07      | 0.74±0.05      | 0.47±0.04      | Undefined      |
| 12 | 0.14±0.04      | 0.24±0.03      | 0.06±0.04      | Red power law ($\alpha_{\text{opt}} = -0.87$) |
| 13 | -0.07±0.07     | 0.54±0.05      | 0.56±0.1       | Red power law ($\alpha_{\text{opt}} = -1.44$) |
| 14 | 0.60±0.07      | 0.54±0.03      | 0.38±0.08      | Undefined      |
| 15 | 0.54±0.08      | 0.63±0.04      | 0.40±0.09      | Red power law ($\alpha_{\text{opt}} = -1.94$) |
| 16 | 0.33±0.04      | 0.44±0.03      | 0.26±0.04      | Red power law ($\alpha_{\text{opt}} = -1.17$) |
| 17 | 0.25±0.02      | 0.40±0.02      | 0.20±0.03      | Red power law ($\alpha_{\text{opt}} = -1.31$) |

**Notes.**—The relation between the relative colors gives the optical continuum shape from the photometry. $\Delta(u - r) > \Delta(g - i) > \Delta(r - z)$ indicates dust, but $\Delta(u - r) < \Delta(g - i) > \Delta(r - z)$ indicates a red power law.

### Table 6

| S/N-dependent Models Applied to XMM-Newton Observations |
|--------------------------------------------------------|
| Model S/N Model Description                                   |
| A............. <4 Cash fit, fixed power law ($\Gamma = 1.9$), Galactic absorption (fixed) |
| B............. 2 < S/N < 4 Cash fit, free power law, Galactic absorption (fixed) |
| C............. >4 $\chi^2$ fit, free power law, Galactic absorption (fixed) |
| D............. >4 $\chi^2$ fit, free power law, Galactic absorption (fixed), intrinsic absorption (free) |
| E............. >25 $\chi^2$ fit, free power law, Galactic absorption (fixed), intrinsic absorption (free), Fe Kα line |

**Note.**—A total of 22 observations cover 17 sources.
| Source ID | Model | XMM ID | $\Gamma$ | $F_{0.5-2.0\text{ keV}}^{b}$ | $F_{2-10\text{ keV}}^{b}$ | $L_{2-10\text{ keV}}^{b}$ | $\chi^{2}/d$ |
|-----------|-------|--------|--------|-----------------|-----------------|-----------------|-------------|
| 1         | A     | 0201290301 | 1.9$^{d}$ | <0.024          | <0.034          | <9.5 x 10$^{41}$ | 1791/1599   |
| 2         | A     | 0200730401 | 1.9     | 0.24            | 0.36            | 5.2 x 10$^{42}$  | 8904/5766   |
| 3a        | A     | 0113060401 | 1.9     | <0.51           | <3.72           | <3.6 x 10$^{43}$ | 1225/1603   |
| 3b        | A     | 0113060201 | 1.9     | 2.25            | 3.10            | 4.8 x 10$^{43}$  | 1018/1614   |
| 4         | A     | 0145450501 | 1.9     | 0.016           | 13.4            | 5.2 x 10$^{43}$  | 1608/1614   |
| 5a        | A     | 0203360401 | 1.9     | 0.32            | 0.46            | 1.3 x 10$^{43}$  | 17119/5749  |
| 5b        | A     | 0203360801 | 1.9     | 0.53            | 0.74            | 2.1 x 10$^{43}$  | 10447/4946  |
| 6         | A     | 0096560201 | 1.9     | 0.52            | 2.96            | 3.2 x 10$^{43}$  | 1831/1636   |
| 7         | C     | 0091410101 | 1.80.5  | 1.95            | 3.05            | 7.7 x 10$^{43}$  | 4.36        |
| 8         | C     | 0110990201 | 1.0+0.4 | 1.36            | 7.49            | 7.0 x 10$^{43}$  | 9.77        |
| 9a        | C     | 0110930401 | 1.4+0.4 | 2.78            | 7.96            | 1.3 x 10$^{44}$  | 2.65        |
| 9b        | C     | 0110930901 | 1.0+0.4 | 4.57            | 27.2            | 2.7 x 10$^{44}$  | 3.77        |
| 10        | C     | 0096560201 | 1.9+0.4 | 3.05            | 4.90            | 9.4 x 10$^{43}$  | 2.65        |
| 11        | C     | 0143650901 | 1.5+0.3 | 5.03            | 13.3            | 1.5 x 10$^{44}$  | 5.99        |
| 12        | C     | 0149900201 | 1.4+0.4 | 8.58            | 16.2            | 3.0 x 10$^{44}$  | 8.115       |
| 13        | C     | 0081340201 | 1.6+0.1 | 9.59            | 20.7            | 2.8 x 10$^{44}$  | 27.40       |
| 14        | C     | 0203361801 | 1.75+0.09 | 6.52           | 11.9            | 1.6 x 10$^{44}$  | 54.63       |
| 15        | C     | 0203361801 | 1.78+0.06 | 17.0           | 29.5            | 3.4 x 10$^{44}$  | 75.107      |
| 16a       | C     | 0147511701 | 1.77+0.06 | 12.1           | 20.1            | 2.9 x 10$^{44}$  | 100/165     |
| 16b       | C     | 0147511801 | 1.72+0.05 | 13.2           | 23.5            | 3.2 x 10$^{44}$  | 155/189     |
| 17a       | C     | 0143150301 | 1.68+0.05 | 60.6           | 120             | 1.8 x 10$^{45}$  | 94/142      |
| 17b       | C     | 0143150601 | 1.72+0.03 | 57.9           | 107             | 1.7 x 10$^{45}$  | 203/311     |

\[\text{Fluxes are determined from the MOS-1 observations because it has the best (most well known) calibration.}\]

\[\text{Luminosities are in rest frame.}\]

\[\text{This column contains either the } \chi^{2} \text{ value and the degrees of freedom when } \chi^{2} \text{ statistics are applied (model C) or the likelihood of fit and the degrees of freedom when the Cash statistic is applied (model A).}\]

\[\text{\(\Gamma\) is fixed to 1.9 for model A.}\]

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**TABLE 8**

**ALTERNATIVE X-RAY SPECTRAL FITS:** $\Gamma$ (S/N < 4) AND $N_{H,X}$ (S/N > 4)

| Model | Source ID | XMM ID | $\Gamma$ | $N_{H,X}$ | $\chi^{2}/d$ |
|-------|-----------|--------|--------|----------|-------------|
| B     | 2         | 0200730401 | 1.8+0.4 | 8949/5767 |
| 3a    | 0113060401 | 1.2-2.3   | ...    | 1015/1614 |
| 4     | 0145450501 | 1.2+0.8   | ...    | 1418/1619 |
| 5a    | 0203360401 | 2.0+0.6   | ...    | 17008/5750 |
| 5b    | 0203360801 | 2.5+0.5   | ...    | 11003/4946 |
| 6     | 0096560201 | 1.2+0.3   | ...    | 1822/1636 |
| D     | 7         | 0039140101 | 1.8+0.3 | 8.05      |
| 8     | 0110990201 | 1.0+0.4   | <13.4  | 2.64      |
| 9a    | 0110930401 | 1.4+0.4   | <6.8   | 3.5/5     |
| 9b    | 0110930901 | 1.0+0.4   | <10.2  | 3.6/6     |
| 10    | 0096560201 | 1.9+0.3   | <3.3   | 2.2/5     |
| 11    | 0143650901 | 1.5+0.3   | <0.9   | 5.9/8     |
| 12    | 0149900201 | 1.4+0.4   | <0.8   | 7.3/14    |
| 13    | 0081340201 | 1.6+0.1   | <0.2   | 27/39     |
| 14    | 0203361801 | 1.75+0.09 | <0.5   | 54/62     |
| 15    | 0203361801 | 1.76+0.07 | <0.5   | 75/106    |
| 16a   | 0147511701 | 1.77+0.06 | <0.6   | 100/164   |
| 16b   | 0147511801 | 1.73+0.06 | <0.4   | 155/188   |
| 17a   | 0143150301 | 1.68+0.05 | <0.4   | 94/141    |
| 17b   | 0143150601 | 1.73+0.04 | <0.2   | 203/310   |

**NOTES.—** For sources with S/N < 4, model parameters from the model B (Cash power law) fits are given. For sources with S/N > 4, we list 90% confidence upper limits on model D, power law plus intrinsic absorption.

\[\text{This column contains either the } \chi^{2} \text{ value and the degrees of freedom when } \chi^{2} \text{ statistics are applied (model C) or the likelihood of fit and the degrees of freedom when the Cash statistic is applied (model A).}\]
There is a weak correlation between $c_{ox}$ and $\Gamma$ (Spearman rank of 0.13) such that X-ray-weak objects are slightly more likely to have flatter spectral slopes.

4. DISCUSSION

The redshift selection minimizes the chance that host galaxy emission or Ly$\alpha$ forest absorption produces the observed red colors of these quasars. This leaves two possible causes of red colors: dust reddening or intrinsically red optical continua. Table 11 summarizes the source characteristics of the SDSS/XMM-Newton red quasar sample, which guide the classification of a source as “absorbed” or “intrinsically red.” We discuss dust-reddened quasars in § 4.1 and intrinsically red quasars in § 4.2. In § 4.3 we discuss two quasars that we were not able to classify. We comment on the
general properties of the red sample in terms of the $\alpha_{\text{ox}}-L_{\text{x-ray}}$ relation (§ 4.4) and the X-ray spectral slope (§ 4.5). Finally, we discuss properties of the intrinsically red quasars in § 4.6.

4.1. Dust-reddened Quasars with X-Ray Absorption

By the criteria shown in Table 11, 8 of 17 quasars in the sample are dust reddened. $E(B-V)_{\text{spec}}$ is significant at $\geq 3\sigma$ for all eight sources. Seven of 8 sources have optical continuum shapes consistent with dust-reddened curvature. [The exception, SDSS J1114+5315 (source 11), has larger errors on the relative colors, resulting in an ambiguous continuum shape. However, strong $E(B-V)_{\text{spec}}$ and X-ray weakness argue in favor of dust reddening.]

SDSS J0944+0410 (source 1) is a low-ionization BAL quasar (Voit et al. 1993), with Si IV, C IV, C III, C II], and Mg II absorption troughs of widths $\sim$2000–5000 km s$^{-1}$ (Fig. 2). BALs are known to be heavily absorbed in the optical and the X-rays (Green et al. 2001). This source is undetected in the X-rays (upper limit in Fig. 4). Due to the numerous absorption lines and a strong Fe II bump, we were not able to fit a reddening to the spectral continuum, so the flatness of the spectrum could be due to either line absorption, continuum absorption, or an intrinsically different continuum. However, some research suggests that BALs tend to have redder continua than non-BALs, and dust-reddened templates appear to be a good fit to BAL continua (Yamamoto & Vansevicius 1999; Brotherton et al. 2001; Tolea et al. 2002; Reichard et al. 2003). We therefore conclude that this quasar is likely to have dust reddening and X-ray absorption.

All eight sources match some of the criteria for X-ray absorption. For the three sources with $2 < S/N < 4$ (where X-rays are detected but no X-ray spectral fits can be made), all are X-ray weak when the optical luminosity is corrected for dust reddening ($\alpha_{\text{ox,corr}} < -1.8$). These sources are discussed further in § 4.4.

Four of the 8 dust-reddened quasars have X-ray $S/N > 4$, which allows us to fit a power law (model C) and a power law plus intrinsic absorption (model D). All four sources prefer model C over model D, but two quasars have abnormally flat ($\Gamma < 1.5$) photon indices to 90% confidence: SDSS J1226+0130 (source 8) and SDSS J1435+4841 (source 9). This may be a sign of large $N_{\text{H}}$ columns. In addition, the upper limits on $N_{\text{H}}$ for all four sources are rather high ($9 \times 10^{21} - 1 \times 10^{23}$ cm$^{-2}$; Table 8) and are consistent with the gas column predicted from $E(B-V)_{\text{spec}}$ ($N_{\text{H, opt}} = 7.0 \times 10^{20} - 1 \times 10^{21}$ cm$^{-2}$) using the Galactic gas-to-dust ratio (Bohlin et al. 1978; Kent et al. 1991). Even the 10 times higher $N_{\text{H}}$ expected from an SMC gas-to-dust ratio (Issa et al. 1993).
TABLE 10
X-Ray Strength Relative to the Optical

| ID      | \(10^{-28} F_{\text{ox}}^a\) (ergs cm\(^{-2}\) s\(^{-1}\) Hz\(^{-1}\)) | \(10^{-28} F_{\text{ox,corr}}^b\) (ergs cm\(^{-2}\) s\(^{-1}\) Hz\(^{-1}\)) | \(10^{-32} F_{2\text{keV}}^c\) ergs cm\(^{-2}\) s\(^{-1}\) Hz\(^{-1}\)) | \(10^{-32} F_{2\text{keV,corr}}^d\) ergs cm\(^{-2}\) s\(^{-1}\) Hz\(^{-1}\)) | \(\alpha_{\text{ox}}\) | \(\alpha_{\text{ox,corr}}^e\) |
|---------|------------------------------------------------|------------------------------------------------|---------------------------------|---------------------------------|----------------|----------------|
| 1........... | 3.87 | 6.04 | \(\leq 2.45\) | \(\leq 2.45\) | \(\leq 1.61\) | \(\leq 1.69\) |
| 2........... | 3.19 | 3.99 | 0.33 | 0.33 | \(-1.91\) | \(-1.95\) |
| 3a........... | 4.39 | 7.54 | \(\leq 0.17\) | \(\leq 0.17\) | \(-2.07\) | \(-2.16\) |
| 3b........... | 4.39 | 7.54 | 3.08 | 3.08 | 0.39 | 0.38 | -1.86 | -1.92 |
| 4........... | 2.85 | 15.05 | 2.81 | 2.81 | \(-1.54\) | \(-1.82\) |
| 5a........... | 2.69 | 3.83 | 0.38 | 0.38 | \(-1.86\) | \(-1.92\) |
| 5b........... | 2.69 | 3.83 | 0.67 | 0.67 | \(-1.77\) | \(-1.83\) |
| 6........... | 5.00 | 15.66 | 29.0 | \(-1.52\) | \(-1.27\) |
| 7........... | 2.53 | 5.82 | 2.75 | 2.75 | \(-1.87\) | \(-1.66\) |
| 8........... | 5.65 | 15.34 | 7.24 | 7.24 | \(-1.55\) | \(-1.17\) |
| 9a........... | 2.10 | 5.06 | 45.1 | \(-1.55\) | \(-1.17\) |
| 9b........... | 2.10 | 5.06 | 3.67 | 3.67 | \(-1.61\) | \(-1.59\) |
| 10........... | 2.64 | 5.67 | 10.0 | \(-1.45\) | \(-1.44\) |
| 11........... | 5.34 | 17.66 | 4.57 | 4.57 | \(-1.56\) | \(-1.66\) |
| 12........... | 7.39 | 9.88 | 7.36 | 7.36 | \(-1.54\) | \(-1.52\) |
| 13........... | 1.33 | 2.64 | 9.72 | 9.72 | \(-1.20\) | \(-1.30\) |
| 14........... | 2.20 | 5.09 | 7.79 | 7.79 | \(-1.32\) | \(-1.46\) |
| 15........... | 2.21 | 6.47 | 22.6 | 22.6 | \(-1.15\) | \(-1.33\) |
| 16a........... | 4.42 | 9.48 | 14.7 | 14.7 | \(-1.33\) | \(-1.45\) |
| 16b........... | 4.42 | 9.48 | 15.2 | 15.2 | \(-1.33\) | \(-1.45\) |
| 17a........... | 53.67 | 95.96 | 63.5 | 63.5 | \(-1.51\) | \(-1.60\) |
| 17b........... | 53.67 | 95.96 | 64.4 | 64.4 | \(-1.51\) | \(-1.60\) |

\(^a\) Rest-frame 2500 Å fluxes. 
\(^b\) The 2500 Å flux is corrected using \(E(B-V)_{\text{spec}}\). 
\(^c\) Rest-frame 2 keV fluxes. 
\(^d\) For sources with \(S/N > 4\), the 2 keV flux is corrected for the \(N_{\text{H}}\) 90% confidence upper limit. (No 2 keV flux correction is made for sources with IDs 1–7.) 
\(^e\) Parameter \(\alpha_{\text{ox,corr}}\) is calculated with \(F_{\text{ox,corr}}\) and \(F_{2\text{keV,corr}}\) so that it is corrected for dust reddening and, where possible, an upper limit on X-ray absorption.

Fig. 4.—\(\alpha_{\text{ox}}\) vs. \(l_{\text{ox}}\) for the red quasar sample, where \(l_{\text{ox}}\) is the log of the 2500 Å luminosity in units of ergs cm\(^{-2}\) s\(^{-1}\) Hz\(^{-1}\). The open circles give the measured \(l_{\text{ox}}\) and \(\alpha_{\text{ox}}\) values for the red quasar sample. The filled circles give \(l_{\text{ox,corr}}\) and \(\alpha_{\text{ox,corr}}\), where the 2500 Å flux has been corrected for \(E(B-V)_{\text{spec}}\) and the 2 keV flux has been corrected for the upper limit on \(N_{\text{H}}\). The six sources with X-ray \(S/N < 4\) are corrected for \(E(B-V)_{\text{spec}}\) only and not \(N_{\text{H}}\), these sources are marked in red. The S06 \(\alpha_{\text{ox}}l_{\text{ox}}\) correlation is plotted as a solid line, and the S05 sample is overplotted in black points. The dotted line marks \(\alpha_{\text{ox}} = -1.8\). Sources with \(\alpha_{\text{ox}} < -1.8\) are defined to be X-ray weak. The legend shows the correction to \(\alpha_{\text{ox}}\) and \(l_{\text{ox}}\) for an \(E(B-V)_{\text{spec}} = 0.1\) and the correction to \(\alpha_{\text{ox}}\) for an \(N_{\text{H}}\) upper limit of 10\(^2\) cm\(^{-2}\). Both of the corrections shown in the legend were calculated for the sample’s median redshift, \(z = 1.3\).

4.2. Intrinsically Red Quasars

Seven sources display mild or insignificant dust reddening: \(E(B-V)_{\text{spec}} \leq 0.1\) or \(E(B-V)_{\text{spec}}\) detected at \(< 3\) \(\sigma\). Since the reddening in these sources is indistinguishable from a red power law (§3.2), we classify them as intrinsically red using two additional indicators: (1) the continuum shape as determined by the relative photometry (§3.2) and (2) the lack of X-ray absorption (§3.4).

The optical continuum shape is inconsistent with dust reddening for all but one object. The relative colors for SDSS J0959+0209 (source 14) cannot distinguish between dust curvature and a red power law; however, this source meets all of the other intrinsically red criteria. Six of seven sources also display no significant X-ray absorption, with low \(N_{\text{H}}\) upper limits of \(\sim 10^{20}$–$10^{21}$ cm\(^{-2}\). These same six sources are X-ray normal (\(\alpha_{\text{ox,corr}} > -1.8\)) and are not abnormally X-ray flat (\(\Gamma > 1.5\) to 90% confidence). It is not surprising then that these six sources have the highest X-ray \(S/N\) of the red quasar sample, due to the absence of X-ray absorption. The exception is SDSS J1002+0203 (source 5), whose low \(S/N\) (\(S/N = 2.85\)) prohibits fitting a power law or intrinsic absorption. This source is X-ray weak (\(\alpha_{\text{ox}} = -1.82\)).
reddening. The criteria for X-ray absorption are (a) a strong spectroscopic reddening [E(B − V)\text{spec} > 0.1] detected at >3σ confidence and (b) an optical continuum shape that indicates dust reddening. The criteria for X-ray absorption are (a) weak X-ray flux relative to the optical (α\text{ex} < −1.8), (b) a flat X-ray spectral slope (Γ < 1.5 to greater than 90% confidence), and (c) a large gas column upper limit (N\text{H} upper limit > 10^{22} cm\(^{-2}\)) if intrinsic absorption fits are applied. For intrinsically red quasars, a value is boldfaced if the source matches one of the criteria of an intrinsically red power law: (a) reddening is mild [E(B − V)\text{spec} < 0.1] or detected at <3σ, (b) an optical continuum shape that contradicates dust reddening, (c) a low X-ray gas column upper limit (N\text{H} upper limits < 10^{21} cm\(^{-2}\)), and (d) gas/dust ratio smaller than the Galactic value.

For the four sources with the highest X-ray S/N, SDSS J0959+0209 (source 14), SDSS J0958+0213 (source 15), SDSS J1053+5735 (source 16), and SDSS J0913+5259 (source 17), the low N\text{H} upper limits imply gas-to-dust ratio upper limits (Table 8) up to a factor of ~2 smaller than the Galactic value (Bohlin et al. 1978; Kent et al. 1991) and a factor of ~20 below the SMC value (Issa et al. 1990) (Fig. 5). The small gas-to-dust ratio found for these four objects contrasts with previous studies, which have shown that an SMC-type extinction curve and high gas-to-dust ratio are most appropriate for quasar absorption (Maccacaro & Perola 1981; Maiolino et al. 2001; Wilkes et al. 2002). For example, Maiolino et al. (2001) collected X-ray and optical information for 19 objects from the literature. They find gas-to-dust ratios 3–100 times higher than Galactic for 16 AGNs. The three AGNs with gas-to-dust ratios a factor of ~1.5 below the Galactic value were all low-luminosity AGNs (L_X < 10^{42} ergs s\(^{-1}\)). For comparison, all of the red quasars have L_X > 10^{42} ergs s\(^{-1}\), with the exception of the BAL quasar (source 1). The smaller filled circles in Figure 5 mark points from Maiolino et al. (2001). Median error bars are displayed on one of the Maiolino et al. (2001) points.

### Table 11

| ID     | SDSS Name     | Γ     | α_{ex,corr} | N_{H\text{X}} (10^{21} cm\(^{-2}\)) | E(B − V)\text{spec} | N_{H\text{X}}/E(B − V)_{\text{spec}} | Optical Continuum | Notes    |
|--------|---------------|-------|-------------|-----------------------------------|----------------------|-------------------------------------|------------------|---------|
| 1...... | SDSS J0944−0410 | 1.9   | ≤−1.69      | ...                               | ...                  | ...                                 | Dust BAL         |         |
| 3...... | SDSS J1652+3947 | 1.9   | −1.92       | ...                               | 0.08±0.02            | ...                                 | Dust             |         |
| 4...... | SDSS J0728+3708 | 1.9   | −1.82       | ...                               | 0.25±0.02            | ...                                 | Dust             |         |
| 6...... | SDSS J2217−0823 | 1.9   | −2.31       | ...                               | 0.17±0.02            | ...                                 | Dust             |         |
| 7...... | SDSS J1533+5243 | 1.8   | 0.05        | ≤−1.27                           | 0.12±0.01            | ≤100                                | Dust             |         |
| 8...... | SDSS J1126+0130 | 1.0   | 0.04        | ≤−1.66                           | 0.15±0.01            | ≤143                                | Dust NAL         |         |
| 9...... | SDSS J1435+4841 | 1.2   | 0.03        | ≤−6.8                            | 0.13±0.01            | ≤100                                | Dust NAL         |         |
| 11...... | SDSS J1114+5315 | 1.5   | 0.03        | ≤0.9                             | 0.18±0.03            | ≤8                                  | Undefined        |         |
| 5...... | SDSS J1102+0203 | 1.9   | 1.87        | ...                               | 0.052±0.005          | Red power law                       |                   |         |
| 12...... | SDSS J1135+4900 | 1.4   | 0.04        | −1.52                            | 0.04±0.01            | ≤20                                 | Red power law    |         |
| 13...... | SDSS J1254+5649 | 1.6   | 0.30        | ≤0.2                             | 0.10±0.01            | ≤3                                  | Red power law    |         |
| 14...... | SDSS J0958+0209 | 1.75  | 0.09        | ≤0.6                            | 0.12±0.03            | ≤6                                  |Undefined          |         |
| 16...... | SDSS J1053+5735 | 1.75  | 0.04        | ≤0.06                            | 0.11±0.02            | ≤9                                  | Red power law    |         |
| 17...... | SDSS J0913+5259 | 1.70  | 0.03        | ≤0.03                            | 0.086±0.003          | ≤6                                  | Red power law    |         |

**Notes.**—For absorbed quasars, a value is boldfaced if the source matches one of the criteria for dust reddening in the optical/UV or absorption in the X-rays. Criteria for dust reddening are (a) strong spectroscopic reddening [E(B − V)_{\text{spec}} > 0.1] detected at >3σ confidence and (b) an optical continuum shape that indicates dust reddening. The criteria for X-ray absorption are (a) weak X-ray flux relative to the optical (α_{ex} < −1.8), (b) a flat X-ray spectral slope (Γ < 1.5 to greater than 90% confidence), and (c) a large gas column upper limit (N\text{H} upper limit > 10^{22} cm\(^{-2}\)) if intrinsic absorption fits are applied. For intrinsically red quasars, a value is boldfaced if the source matches one of the criteria of an intrinsically red power law: (a) reddening is mild [E(B − V)_{\text{spec}} < 0.1] or detected at <3σ, (b) an optical continuum shape that contradicates dust reddening, (c) a low X-ray gas column upper limit (N\text{H} upper limits < 10^{21} cm\(^{-2}\)), and (d) gas/dust ratio smaller than the Galactic value.

a Parameter α_{ex,corr} is calculated with F_{\text{ex,corr}} and F_{2keV,corr} so that it is corrected for dust reddening and, where possible, for X-ray absorption upper limits.

b The measured gas/dust ratio relative to the Galactic value, 5.8 × 10^{21} cm\(^{-2}\) (Bohlin et al. 1978; Kent et al. 1991).

c The optical continuum shape is defined by the relationship between the relative colors (§ 3.4, Table 5).

but the low amount of dust reddening [E(B − V)_{\text{spec}} = 0.052 ± 0.005] suggests that the X-ray weakness is intrinsic. If we assume an SMC gas/dust ratio, then a reddening of 0.05 leads to an X-ray absorption column of N\text{H} = 3 × 10^{21} cm\(^{-2}\). However, a column of less than 10^{22} cm\(^{-2}\) will not significantly affect the rest-frame 2 keV flux (Tucker 1975).

For the four sources with the highest X-ray S/N, SDSS J0959+0209 (source 14), SDSS J0958+0213 (source 15), SDSS J1053+5735 (source 16), and SDSS J0913+5259 (source 17), the low N\text{H} upper limits imply gas-to-dust ratio upper limits (Table 8) up to a factor of ~2 smaller than the Galactic value (Bohlin et al. 1978; Kent et al. 1991) and a factor of ~20 below the SMC value (Issa et al. 1990) (Fig. 5). The small gas-to-dust ratio found for these four objects contrasts with previous studies, which have shown that an SMC-type extinction curve and high gas-to-dust ratio are most appropriate for quasar absorption (Maccacaro & Perola 1981; Maiolino et al. 2001; Wilkes et al. 2002). For example, Maiolino et al. (2001) collected X-ray and optical information for 19 objects from the literature. They find gas-to-dust ratios 3–100 times higher than Galactic for 16 AGNs. The three AGNs with gas-to-dust ratios a factor of ~1.5 below the Galactic value were all low-luminosity AGNs (L_X < 10^{42} ergs s\(^{-1}\)). For comparison, all of the red quasars have L_X > 10^{42} ergs s\(^{-1}\), with the exception of the BAL quasar (source 1). The smaller filled circles in Figure 5 mark points from Maiolino et al. (2001). Median error bars are displayed on one of the Maiolino et al. (2001) points.
The unusually low apparent gas-to-dust ratios for the four high X-ray S/N objects (sources 14–17) suggest that dust reddening and X-ray absorption are not applicable in these cases. We therefore take the unusually low gas-to-dust ratios of these four sources to be another indicator of an intrinsically red continuum.

The intrinsically red classification is shown in Fig. 6, where we plot the gas/dust ratio, \(N_{\text{H}} \times E(B-V)_{\text{spec}}\), against \(\Delta(u-r) - \Delta(g-i)\) color. The vertical dotted line at \(\Delta(u-r) - \Delta(g-i) = 0\) divides the quasars with dust-reddened continuum shapes from the quasars with red power-law continua, as discussed in § 3.4. The horizontal dashed line shows where the gas/dust ratio equals the Galactic value; sources below this line have unusually low gas/dust ratios and therefore are considered intrinsically red (§ 4.2). Sources ultimately classified as dust reddened are plotted as open circles, while sources classified as intrinsically red are plotted as filled squares. The unclassified source (source 10, § 4.3) is plotted as a star.

4.3. Unclassified Quasars

The classification of two quasars is undetermined. SDSS J0232−0731 (source 2) is X-ray weak (\(\alpha_{\text{ox}} = -1.95\)), but the signal is too weak to fit \(\Gamma\) or intrinsic absorption (S/N = 3.23). Dust reddening is mild and is significant only at 1.5 \(\sigma\) \([E(B-V)_{\text{spec}} = 0.03 \pm 0.02]\). However, the optical continuum shape is consistent with dust-type curvature (Table 5).

SDSS J2217−0812 (source 10) is also ambiguous because, while it has normal \(\Gamma\) and \(\alpha_{\text{ox,corr}}\) values \((\Gamma = 1.9^{+0.4}_{-0.3}, \alpha_{\text{ox,corr}} = -1.44)\), the upper limit on \(N_{\text{H}}\) is fairly high at \(1.8 \times 10^{22} \text{ cm}^{-2}\), and the gas-to-dust ratio upper limit is between the Galactic and SMC values. The optical continuum shape is consistent with both dust-reddened curvature and a red power law within the photometric error bars on the relative colors. While absorption is not specifically indicated, it also cannot be ruled out.

4.4. Red Quasars and the \(\alpha_{\text{ox}}-I_{\text{uv}}\) Relation

Several studies (Avni & Tananbaum 1982; Vignali et al. 2003; S05; Steffen et al. 2006) have investigated an anticorrelation between \(\alpha_{\text{ox}}\) and \(I_{\text{uv}}\) (the log of the 2500 \(\AA\) luminosity) in radioquiet quasars. Figure 4 (described in § 3.2) shows that the majority of the sample is consistent with the S05 \(\alpha_{\text{ox}}-I_{\text{uv}}\) sample. Five sources, however, are X-ray weak, even after a correction for \(E(B-V)_{\text{spec}}\) is applied, and appear inconsistent with the S05 \(\alpha_{\text{ox}}-I_{\text{uv}}\) sample. All five have S/N < 4, so no correction can be made for \(N_{\text{H}}\).

We have made a statistical comparison between the red quasar sample and the S05 sample. The S05 sample was selected from the SDSS using Data Release 2 photometry, so aside from updates to the SDSS quasar selection process between DR2 and DR3, the S05 quasar selection is the same as that of the red quasar sample, except for the red color cut. We simplified the comparison of the two samples by noting that the red sample luminosity is spread over a single decade, and for S05, \(\alpha_{\text{ox}}\) changes by only 0.16 in this luminosity range. We thus restricted the luminosity range of both samples so that we could apply the one-dimensional Kolmogorov-Smirnov (K-S) test. The observed luminosity range of both the red quasar and the S05 samples is restricted to \(I_{\text{uv}} = 29.4-30.3\) when comparing the corrected red quasar sample (Fig. 4, open circles) to the S05 sample. Since correcting \(\alpha_{\text{ox}}\) for dust reddening shifts the UV luminosity to a brighter interval, we restrict the luminosity range to \(I_{\text{uv}} = 29.7-30.8\) when comparing the corrected red quasar sample (Fig. 4, filled circles) to the S05 sample. This excludes only one member of the red quasar sample (source 17).
First, we compare the complete red quasar sample (excluding the high-$\alpha_{\text{X}}$ source 17) with the S05 sample. We find a K-S probability of 0.02% that the two samples come from the same parent population. Next, we consider only the 11 sources for the K-S test where we were able to correct for X-ray absorption (i.e., S/N > 4; black circles in Fig. 4), so that we can compare the uncorrected and corrected $\alpha_{\text{X}}$-$\lambda_{\text{X}}$ distributions to the S05 sample. Comparing first the uncorrected red quasar sample to the S05 sample, we find a probability of 10% that the two samples come from the same parent population. Then we compare the corrected red quasar sample to the S05 sample, and we find a K-S probability of 76%.

Six of 11 quasars with S/N > 4 are intrinsically red, so this suggests that intrinsically red quasars are not intrinsically X-ray weak compared to typical quasars, with the exception of SDSS J1002+0203 (source 5). However, their peculiar SEDs make the physical interpretation unclear.

For sources with S/N < 4, it is plausible that correcting for absorption would significantly increase the K-S probability if the low S/N is due to large $N_{\text{H}}$ columns. We find that if we apply a uniform correction to all of the low-S/N quasars, an absorption column of $N_{\text{H}} > 10^{23} \text{ cm}^{-2}$ is required to achieve a K-S probability of at least 1% that the red quasar sample is drawn from the same parent population as the S05 sample.

4.5. X-Ray Power-Law Index

The mean X-ray photon index for sources with S/N > 4 is $\langle \Gamma \rangle = 1.58 \pm 0.09$, with an intrinsic dispersion $\sigma_{\Gamma} = 0.3$. Figure 8 plots $\Gamma$ versus S/N for each source with S/N > 4, with the mean $\Gamma$ plotted as a solid line for reference, and the intrinsic dispersion plotted as dashed lines. For sources with multiple observations, the photon indices are averaged and the error plotted is the rms of the measured errors.

The mean $\Gamma$ in this sample is flatter than that of other samples of quasar X-ray spectra, including *XMM-Newton* samples. For example, Mateos et al. (2005) found a weighted mean $\langle \Gamma \rangle = 1.96 \pm 0.01$ with an intrinsic dispersion $\sigma_{\Gamma} = 0.4$ for 1137 serendipitously selected *XMM-Newton* AGNs. An investigation of 86 bright AGNs detected in the *XMM-Newton* COSMOS field (Mainieri et al. 2007) gives $\langle \Gamma \rangle = 2.08 \pm 0.08$, with an intrinsic dispersion $\sigma_{\Gamma} = 0.24$. The two surveys are consistent within errors. These mean values are plotted as dotted lines for reference in Figure 8.

The measurement of $N_{\text{H}}$ can affect the measurement of $\Gamma$. The contour plots in Figure 3 show that the two variables are correlated so that the same spectrum may be fitted with a large $N_{\text{H}}$ column and steep $\Gamma$, or with a smaller $N_{\text{H}}$ column and flatter $\Gamma$. Therefore, the flatter mean $\Gamma$ may be due to the effect of $N_{\text{H}}$ on the X-ray spectra with lower S/N. Because the sources with higher X-ray S/N have tighter upper limits, the $\Gamma-N_{\text{H}}$ correlation is less noticeable for these sources (e.g., Fig. 3, sources 14, 15, 16, and 17).

Considering only the intrinsically red group (squares in Fig. 8), excluding source 5 due its low X-ray S/N, we find a mean $\Gamma = 1.66 \pm 0.08$, with an intrinsic dispersion of only $\sigma_{\Gamma} = 0.06$. This tight intrinsic dispersion shows that most of the variance in the intrinsically red group comes from measurement errors. Since the contour plots in Figure 3 show that $\Gamma$ and $N_{\text{H}}$ are not strongly correlated for any of the intrinsically red quasars, the flatter X-ray spectra cannot be explained by absorption.

A significantly flatter $\Gamma$ may be explained via relation to other quantities. The X-ray spectral slope of normal quasars does not depend on optical luminosity or redshift (Shemmer et al. 2005; Vignali et al. 2005) but does depend slightly on X-ray luminosity (Dai et al. 2004; Saez et al. 2008). However, the $\Gamma-L_X$ correlation contains too much intrinsic scatter (e.g., Fig. 8 of Saez et al. 2008) to make conclusive statements about the intrinsically red quasars. The $\Gamma-L_X$ correlation is not significant in the red quasar sample.

The strongest correlation reported between X-ray parameters and other variables is between $\Gamma$ and the H/β emission line FWHM, where flatter X-ray spectral slopes correlate with broader emission lines (Laor et al. 1997; Shemmer et al. 2006). The H/β emission line width is in turn believed to be anticorrelated with the accretion rate (Boroson & Green 1992; Brandt & Boller 1998). Narrow-line Seyferts 1s (NLS1’s) lie on one end of the $\Gamma-H/\beta$ correlation, with steep X-ray spectral slopes, narrow H/β lines (Brandt & Boller 1998; Grupe 2004), and accretion rates close to the Eddington rate (Komossa 2008). While the H/β line is not visible in the optical spectra for the red quasar sample, the broad Mg II line is visible in all of the intrinsically red spectra and has an ionization potential similar to H/β and an FWHM that correlates well with FWHM(H/β) (McLure & Jarvis 2002). The Mg II line widths of all the red quasars are broader than average (Fig. 9). This may be
due to our color and redshift selection criteria, which biases the red quasar sample toward objects with strong Mg ii lines. However, the unabsorbed, flat X-ray spectral slopes combined with the broad Mg ii lines put the intrinsically red quasars on the correlation at the opposite end from NLS1’s (Fig. 10).13 NLS1’s are believed to have accretion rates close to the Eddington rate because of their narrow Hβ lines and steep X-ray spectra (Komossa 2008). Steep red optical/UV continua seem to be an effective means of selecting an extreme red population opposite NLS1’s.

4.6. Properties of Intrinsically Red Quasars

In this section we investigate the basic properties of the intrinsically red quasars: their black hole masses (MBH) and accretion rates (M). These values, and the values from which they are derived, are listed in Table 12. The black hole masses are calculated by assuming virial motion of the broad-line clouds around the central black hole, an assumption justified from reverberation mapping (Peterson & Wandel 2000; Onken & Peterson 2002). The FWHM of the broad Mg ii line can then be used to determine the black hole mass using the following equation from McLure & Jarvis (2002):

\[
\frac{M_{\text{BH}}}{M_\odot} = 3.37 \left( \frac{\Delta L_{3000}}{10^{37}} \right)^{0.47} \left( \frac{\text{FWHM(Mg ii)}}{\text{km s}^{-1}} \right)^2.
\]

The luminosity at 3000 Å (L3000) gives the radius of the broad-line region (BLR) as determined by the RBLR–L relation obtained from reverberation studies (e.g., Kaspi et al. 2000; Bentz et al. 2006). This relation was derived for a normal BBB-dominated SED. Since the BBB appears to be missing from the intrinsically red quasars, the ionizing continuum may be lower than normal; this would result in an overestimate of the black hole mass. Shang et al. (2005) show that the BBB peaks at ~1100 Å, so αox is a good estimate of the ionizing continuum. Since the intrinsically red quasars have αox values within the normal range (e.g., Steffen et al. 2006), we can assume that the RBLR–L relation is still valid for the intrinsically red quasars.

The apparent black hole masses for the intrinsically red quasars are relatively high, ranging from ~10⁸ to ~10¹⁰ M_⊙ (e.g., Shen et al. 2008).

We obtain the accretion rate from the bolometric luminosity: Lbol = 2πMc². We assume an efficiency η = 10%. Standard bolometric correction factors (e.g., Elvis et al. 1994; Kaspi et al. 2000) are not reliable for the intrinsically red quasars with their atypical SEDs. Instead, we integrated the optical power law (αopt) from 2500 to 10000 Å, the nominal UV–to–X-ray power law (αox) from 2500 Å to 2 keV, and the X-ray power law (Γ) from 2 to 10 keV to give a rough approximation of the bolometric luminosity. Changing the break point between the two power laws from 2500 Å to, e.g., 1150 Å (Shang et al. 2005), or even to 1000 Å, has a small effect on Lbol. Since object 17 is a lensed quasar, we reduce its luminosity by the modeled magnification factor, M = 15 (Chartas 2000). Although we have no mid-IR data for these quasars, IR emission accounts for ~40% of the bolometric luminosity for a typical quasar SED (Richards et al. 2006). Therefore, if the intrinsically red quasars are similar, the IR emission will not change the total luminosity, and hence the accretion rate, by more than a factor of a few. To constrain this estimate, we searched the IRAS Point Source Catalog and the Faint Source Catalog (FSC) for the red quasars but found no matches. Sources in the FSC14 have flux densities greater than 200 mJy at 60 μm, which gives an upper limit to 2Lbol/(60 μm)/Lbol ≤ 7.0. This constrains the IR emission to be less than an

13 We do not plot the absorbed quasars on this plot because, due to the high N_H upper limits, Γ is not well determined for these objects.

14 See http://irsa.ipac.caltech.edu/IRASdocs/surveys/fsc.html.

| ID   | SDSS Name   | FWHM(Mg ii) (km s⁻¹) | M_{BH} (10⁶ M_⊙) | L_{bol} (10⁴⁵ erg s⁻¹) | M / (M_⊙ yr⁻¹) | M/M_{Edd} |
|------|-------------|----------------------|------------------|-----------------------|----------------|------------|
| 5    | SDSS J1002+0203 | 10800                | 9.1             | 2.5                   | 0.5            | 0.002      |
| 12   | SDSS J1133+4900 | 9100                 | 3.3             | 4.2                   | 0.7            | 0.010      |
| 13   | SDSS J1254+5649 | 8200                 | 0.68            | 1.6                   | 0.3            | 0.019      |
| 14   | SDSS J1059+0209 | 23200                | 9.9             | 1.6                   | 0.3            | 0.001      |
| 15   | SDSS J1058+0213 | 10500                | 1.3             | 2.5                   | 0.5            | 0.015      |
| 16   | SDSS J1103+5735 | 5400                 | 0.76            | 3.4                   | 0.6            | 0.035      |
| 17   | SDSS J1013+5259 | 6000                 | 3.9             | 2.6                   | 0.5            | 0.005      |

* The accretion rate calculated from L_{bol} = ηMc², where η = 0.1.
order of magnitude of the bolometric luminosity. The estimated bolometric luminosities give a lower bolometric correction compared to previous work. $L_{\text{bol}}/L_{\text{2000}} = 2.6 \pm 1.6$ for the intrinsically red sample, a factor of 2.4 lower than that obtained by Elvis et al. (1994) (6.3 ± 3.1).

Using $L_{\text{bol}}$, we find that the intrinsically red quasars have relatively low accretion rates (Fig. 11). The intrinsically red quasars lie clustered between ~0.001$M_{\text{Edd}}$ and 0.03$M_{\text{Edd}}$. In comparison, typical accretion rates for optically or UV-selected quasars range from $M/M_{\text{Edd}} = 0.03$ to 10.0, with a median value of ~0.6 (Warner et al. 2004; Bonning et al. 2007). The low accretion rates of the intrinsically red quasars are in agreement with their position on the $T$–FWHM($\text{Mg ii}$) correlation (Fig. 10, § 4.5).

5. INTRINSICALLY RED QUASARS: PHYSICAL MODELS

We have found a substantial subset of red quasars whose red colors are probably due to intrinsically red optical emission in the optical/UV rather than dust reddening. This subset comprises a large fraction (7/17 ~ 40%) of SDSS quasars with $(g - r) \geq 0.5$. Note that this is based on color selection; selection via relative colors [e.g., $\Delta(g - i) > 0.35$] would likely change the frequency of intrinsically red quasars because dust-reddened quasars have a redder color distribution than intrinsically red quasars (§ 4.2).

For redshifts $z \sim 1-1.5$, the small blue bump redshifts the observed $g - r$ colors resulting in similar samples, whether selected by color or color excess. However, for redshifts $z \sim 1.5-2$, the $g - r$ color decreases; for this range, selection via color excess would increase the number of quasars with smaller color excesses, thereby possibly increasing the fraction of intrinsically red quasars.

Quasars with intrinsically red SEDs have been discussed before (e.g., Risaliti et al. 2003; Hall et al. 2006; see § 1). For example, the intrinsically red quasars found by Hall et al. (2006) do not show absorption in the optical or X-ray continua, yet they also have steep optical slopes ($\alpha_{\text{opt}} = -1.0$, $\sigma_{\text{opt}} = 0.2$), determined via fits to the SDSS spectra.

Intrinsically steep optical power laws suggest that these quasars have a different continuum emission mechanism from ordinary quasars. We consider three possibilities to explain the red optical power laws: (1) strong synchrotron emission visible in the optical; (2) a high-temperature BBB, which exposes the red power law that may underlie typical optical emission; or (3) a low-temperature BBB resulting from a low accretion rate, such that the steep, high-energy tail of the BBB is visible in the optical.

5.1. Synchrotron Emission

Synchrotron radiation could result in a red optical power law. However, typical synchrotron emission can be discounted for two reasons. First, synchrotron radiation is strongest in the radio, with a turnover frequency at $v_\text{m} = 10^{11}$ Hz (Marscher 1995). Therefore, we would expect strong radio emission in all of the intrinsically red quasars, when in fact only one can be classified as radio-loud (Table 1). Second, even if a higher than normal turnover frequency allowed the synchrotron emission to dominate in the optical, the superposition of synchrotron emission on a BBB would result in a U-shaped spectrum (Fig. 2 of Francis et al. 2000). This is not observed in any of the optical spectra.

5.2. Exposed Underlying Power Law

A red power law is sometimes proposed to underlie the BBB in other quasars (Malkan & Sargent 1982; Ward et al. 1987; Lawrence 2005). If the BBB were removed or diminished, this underlying power law would be exposed. One way of “removing” the BBB is to shift it to higher temperatures. Possible examples of high-temperature BBBS exposing a red, underlying optical power law are known: the NLS1’s RE J1034+396 (Puchnarewicz et al. 1995b) and RE J2248−511 (Puchnarewicz et al. 1995a). In these objects, the optical power-law slopes are $-1.3$ and $-0.9$, respectively. RE J1034+396 is an EUV-selected source with an ultrasoft X-ray excess that peaks near 0.4 keV. The effective maximum temperature of the accretion disk is $T \sim 10^6$ K ($\log T_{\max} \sim 16.8$), more than an order of magnitude hotter than typical quasar accretion disk temperatures ($T \sim 10^{4.5}$ K, $\log T_{\max} \sim 15.3$; Malkan & Sargent 1982). The optical spectrum of this source shows no signs of a BBB. RE J2248−511 also has a high-energy turnover at around 0.25 keV, but a blackbody is a poor fit to the X-ray data.

The presence of an underlying power law may be explained by weak synchrotron emission from an associated jet emitting at a large angle to the line of sight. This synchrotron emission would necessarily be weak for a radio-quiet object, which is why the BBB must be removed or otherwise modified in order for the red power law to be visible in the optical. Alternatively, unsaturated Comptonization of a seed spectrum can produce a power law over seven decades in frequency (e.g., Maraschi et al. 1982).

Assuming a simple model of the accretion disk as a sum of blackbodies, Lawrence (2005) showed that quasar SEDs scale homologously with temperature, such that hotter AGNs have thermal peaks at higher frequencies. If the local temperature of the disk is due to the release of the gravitational binding energy, then the temperature of the accretion disk scales homologously with the accretion rate. Since the $M_{\text{BH}}$ determines the inner radius of the accretion disk, scaling with black hole mass is model dependent and nonhomologous; however, simple models show that a less massive black hole will have a hotter maximum effective disk temperature (Lawrence 2005). Therefore, high accretion rates and/or low black hole masses could shift the BBB to higher temperatures/energies.

Neither high accretion rates nor low black hole masses are observed in the intrinsically red quasars (§ 4.6), but since the SDSS/XMM-Newton red quasars have relatively high redshifts ($z \sim 1-2$), a soft X-ray turnover similar to that found in the Puchnarewicz et al. (1995a, 1995b) objects would be shifted to
~0.4 keV/(1 + z) = 0.1–0.2 keV. This turnover would lie below the observed XMM-Newton EPIC energy band (0.5–10 keV). A hidden BBB in the EUV or soft X-rays would increase the bolometric luminosity, thereby increasing the accretion rates. However, an increase in the ionizing continuum would mean that the black hole mass calculations are underestimates. Since the effective maximum disk temperature goes roughly as $T \propto M^{1/4}M_{\text{BH}}^{1/2}$, a NLS1’s ($M_{\text{BH}} \sim 10^6$–$10^7$ $M_\odot$; Grupe & Mathur 2004) can achieve an effective maximum disk temperature of 10$^6$ K at normal accretion rates, but highly super-Eddington conditions ($L/L_{\text{Edd}} \sim 10^7$) are required for a quasar with $M_{\text{BH}} \sim 10^9$ $M_\odot$ to reach the same temperature. If the black hole masses are underestimates, then even higher accretion rates are required. Therefore, a high-temperature BBB is unlikely to explain the intrinsically red quasars.

5.3. The Tail of a Low-Temperature Big Blue Bump

Low disk temperatures due to low accretion rates and/or large black hole masses should shift the peak of the BBB to longer, near-infrared wavelengths (Frank et al. 2002, p. 90). Our bolometric luminosity estimates for the intrinsically red quasars suggest accretion rates ~10–100 times lower than typical quasars (Fig. 11, § 4.6). The low accretion rate hypothesis is supported by the uniformly flat X-ray spectral slopes and broad Mg ii lines of the intrinsically red quasars (Fig. 10, § 4.5). We can determine the temperature of the thermal peak expected for the calculated accretion rate using the scaling relation developed by Lawrence (2005). A typical quasar has an effective maximum temperature ~10$^{4.8}$ K (Malkan & Sargent 1982); this corresponds to a BBB peak at $\log \nu_{\text{max}} \sim 15.6$. Assuming a conservative accretion rate of 0.1$L_{\text{Edd}}$ for the Elvis et al. (1994) SED, an intrinsically red quasar accreting at a rate lower by a factor of 10 will be a factor of $(10)^{4/3} \sim 1.8$ lower in temperature, so the BBB will peak at $\log \nu_{\text{max}} \sim 15.3$. The most extreme accretion rate ($0.001L_{\text{Edd}}$ source 14) gives a BBB peak at $\log \nu_{\text{max}} \sim 15.1$.

We can model the low disk temperature expected from a low accretion rate using a simple template SED. The CLOUDY package approximates the AGN SED with a toy model (Ferland 2001):

$$F_\nu = A\nu^{-\alpha_\nu}e^{-h\nu/kT_{\text{cut}}} + B\nu^{\alpha_X}.$$  

The A and B constants are normalizations for the optical/UV and X-ray terms, respectively. The UV and X-ray slopes are power laws ($\alpha_\nu$ and $\alpha_X$), where $F_\nu \propto \nu^{\alpha_\nu}$. The high-energy cutoff, $kT_{\text{cut}}$, corresponds to the maximum accretion disk temperature. We performed a qualitative fit, first to the Elvis et al. (1994) SED, and then to the intrinsically red quasar SED. For the Elvis et al. (1994) SED, we use $\alpha_\nu = -0.5$, $\alpha_X = -1$, and $T_{\text{cut}} = 10^{4.8}$ K. For the intrinsically red SEDs, we change $\alpha_X$ to the value obtained in the X-ray fit, and we change $T_{\text{cut}}$ by the amount expected for the lower accretion rate, calculated according to the Lawrence (2005) scaling relation. Since the UV power law defines the rise of the BBB, we do not change $\alpha_\nu$. Figure 12 shows the SED data and model fit for all seven intrinsically red quasars. The figure demonstrates that a lower disk temperature qualitatively reproduces the observed red power law for four objects. Two objects (15 and 16) are better fitted with an accretion rate an
order of magnitude smaller than that shown. A third object (5) is not fitted well by any model.

6. CONCLUSIONS AND FUTURE WORK

We have cross-correlated the SDSS DR3 Quasar Catalog (Schneider et al. 2005) with the XMM-Newton archive, selecting the reddest \((g - r \geq 0.5)\), moderate-redshift \((0.9 < z < 2.1)\) quasars. We obtain a sample of 17 quasars, 16 of which are detected in the X-rays. Using both optical and X-ray data to constrain dust reddening and absorption, we are able to distinguish between obscured and intrinsically red quasars, although two cases remain ambiguous.

Eight quasars are dust reddened in the optical and, while the X-ray data prefer an unabsorbed power law, the upper limits are high enough that X-ray absorption at the level expected from the SMC gas-to-dust ratio is allowed. For the three quasars with high enough X-ray S/N to fit a power-law plus intrinsic absorption model, we obtain upper limits of \(3 \times 10^{22} \text{ cm}^{-2}\). For five sources, the X-ray S/N is too low to fit spectral models. However, we can obtain a lower limit to \(N_H\) by comparing the \(\alpha_{\text{ox}} - \text{FUV}\) distribution of the red quasar sample to that of S05, a recent study of SDSS quasars, where no red color cut is applied. If the two samples come from the same parent distribution, an absorbing column of at least \(10^{23} \text{ cm}^{-2}\) is required for the five low S/N quasars.

Seven quasars display no evidence of X-ray absorption, and dust reddening is contraindicated by the continuum shape as determined by the optical photometry. These quasars seem to form a group with intrinsically red power laws in the optical/UV. It seems that these intrinsically red power laws may be caused by lower accretion rates: low accretion rates are derived from \(M_{\text{BH}}\) and \(L_{\text{bol}}\) estimates, although the \(M_{\text{BH}}\) values may be biased high by the red SEDs. Moreover, the unusually broad Mg \(\text{II}\) emission lines place these quasars on the \(\Gamma - \text{FWHM(Mg \text{II})}\) relation, also suggesting lower accretion rates.

The intrinsically red quasars are a substantial population with extreme characteristics that are well suited to X-ray follow-up. Since seven intrinsically red quasar candidates have been found in the 1% of the SDSS DR3 quasar catalog that overlaps with archival XMM-Newton observations, as many as 700 intrinsically red candidates may exist in the complete catalog. Since the DR6 has more than doubled the number of SDSS quasars, we can expect 1600 intrinsically red quasar candidates, 16 of which have been observed serendipitously with XMM-Newton. The intrinsically red quasar candidates in this paper also merit further observations in order to confirm the lack of dust reddening and pinpoint the physical cause of the red optical power laws. For example, NIR (e.g., JHK) spectra would include H\(\alpha\) and H\(\beta\) and so could give an independent measure of dust reddening via the Balmer decrement. NIR measurements will also constrain a low-temperature disk model, as well as \(L_{\text{bol}}\) and hence \(\dot{M}\). With optical and X-ray spectra already available, the intrinsically red quasar candidates described in this paper are well suited to more complex SED modeling.

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