THE ASTROPHYSICAL JOURNAL, 510:703–709, 1999 January 10

RED PARKES QUASARS: EVIDENCE FOR SOFT X-RAY ABSORPTION

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Received 1998 April 14; accepted 1998 August 18

ABSTRACT

The Parkes Half-Jansky Flat-Spectrum Sample contains a large number of sources with unusually red optical-to–near-infrared (NIR) continua. If this is to be interpreted as extinction by dust in the line of sight, then associated material might also give rise to absorption in the soft X-ray regime. This hypothesis is tested using broadband (0.1–2.4 keV) data from the *ROSAT* All-Sky Survey. Significant ($>3\ \sigma$ confidence level) correlations between the optical (and NIR)–to–soft X-ray continuum slope and optical extinction are found in the data, consistent with absorption by material with metallicity and a range in the gas-to-dust ratio as observed in the local ISM. Under this simple model, the soft X-rays are absorbed at a level consistent with the range of extinctions ($0 < A_V < 6$ mag) implied by the observed optical reddening. Excess X-ray absorption by warm (ionized) gas, (i.e., a warm absorber) is not required by the data.

Subject headings: dust, extinction — ISM: general — quasars: general — X-rays: ISM

1. INTRODUCTION

There have been numerous studies reporting the presence of soft ($\lesssim 2$ keV) X-ray absorption in excess of that expected from the Galaxy toward radio quasars. However, such studies have found very little evidence for associated optical reddening by dust (Elvis et al. 1994). Strong evidence for associated Mg II and soft X-ray absorption in a number of radio-loud quasars has been confirmed (e.g., Mathur et al. 1994; Mathur 1994), although evidence for associated optical extinction in these sources is weak. The lack of associated optical extinction may be due to a selection bias. Since X-ray absorption estimates are derived from spectra that require relatively large X-ray counts, such studies may be biased against sources with low counts due to strong X-ray (and hence optical) absorption. It is also possible that X-ray absorption in most sources is dominated by the presence of warm (ionized) absorbers close to the primary continuum source (Pan, Stewart, & Pounds 1990). These have little broadband effect in the optical bandpass, but may strongly absorb X-ray emission.

If strong optical extinction by dust is known a priori, however, then associated absorption of soft X-rays is expected to be present at some level. Evidence for excess soft X-ray absorption in a number of optically reddened radio quasars has been presented by Kollgaard et al. (1995). These authors claim that their results are strongly model dependent, and are also consistent with explanations other than absorption by associated gas and dust. Their sample size is also too small to support any reasonable conclusions. Evidence for an association was recently reported by Puchnarewicz et al. (1996) for a large sample of Seyfert 1 galaxies and quasars. These authors found a correlation between the optical spectral slope and the optical-to–soft X-ray continuum slope that was consistent with absorption by dusty "cold" gas with column densities of $>10^{21}$ cm^{-2} and approximately Galactic dust abundance.

In this paper, we consider the Drinkwater et al. (1997) sample of flat-spectrum radio sources (hereafter Parkes quasars), a subset of which are known to be optically reddened (Webster et al. 1995; Francis et al. 1998). Unfortunately, very little spectroscopic X-ray data exists for these quasars to constrain absorption gas column densities. Siebert et al. (1998) were able to measure power-law photon indices for 105 sources in the sample. They did not find any evidence for excess soft X-ray absorption in the red sources, but they did find that (at low redshifts) the red quasars had lower soft X-ray luminosities than the blue quasars, and they concluded that the X-ray data support the importance of dust in the reddest quasars.

We reanalyze the soft X-ray (0.1–2.4 keV) *ROSAT* broadband measurements from Siebert et al. (1998) using a different approach. We consider a subsample of 119 out of the 323 sources in the Drinkwater et al. (1997) sample, all of which have contemporaneous B_j and K_n photometry, useful for estimates of spectral slopes. About half of these sources are detected in soft X-rays, and upper limits are available for the remainder. Our analysis uses a simple gas-dust absorption model to explore various correlations involving optical (and NIR)–to–soft X-ray continuum slope and optical reddening. We then use the broadband soft X-ray data to search for such correlations and to determine whether soft X-rays are absorbed at a level consistent with the observed optical reddening.

2. QUASAR SAMPLE AND X-RAY DATA

The Parkes Half-Jansky Flat-Spectrum Sample contains 323 sources and is described in detail by Drinkwater et al. (1997). The sample was initially selected from the Parkes 2.7 GHz Survey (Bolton, Savage, & Wright 1979 and references therein) according to the following criteria: 2.7 GHz radio flux densities $f_{2.7\ \mathrm{GHz}} > 0.5$ Jy, radio spectral indices $\alpha_{2.7}^{5} < 0.5$ (where $f_\nu \propto \nu^{-\alpha}$), Galactic latitude $|b| > 20°$, and B1950 declination $-45° < \delta < +10°$. By selecting flat-spectrum radio sources at high frequency, one introduces bias toward core-dominated quasars, since lobe-dominated quasars and radio galaxies have steeper radio spectra and hence are likely to comprise the majority of detections in low-frequency surveys. On the basis of spectroscopic identification alone, the present sample contains a much higher quasar fraction ($\gtrsim 85\%$) than any existing radio sample, with a broad and flat distribution in redshift to $z \sim 4$.

For the purposes of this paper, we have used sources with contemporaneous photometric measurements in B_j, V, R, I, J, H, and K_n, which are complete for a subsample of 119 "nonextended" sources. These were obtained by P. Francis (1998, private communication; see Whiting et al. 1998) in 1997 April, July, and September, using the ANU 40″ and 2.3 m telescopes. These measurements provide reliable estimates of broadband colors, likely to be unbiased with respect to uncertainties from intrinsic variability. The rms uncertainties based on noise statistics in these magnitudes are <0.2 mag.

Since we are primarily interested in the properties of quasars, only spatially unresolved sources in the optical and near-infrared (NIR) have been considered. All sources that appear extended in B_j and K_n, or with optical spectra showing features characteristic of those seen in normal nearby galaxies, are excluded. We also ensured that the sources have broad emission lines in their optical spectra, with velocity widths >2000 km s^{-1} (at FWHM), typical of normal QSOs. Redshifts are available for all the sources, spanning the range $0 < z \leq 3.9$, most of which are from new spectroscopic observations (see Drinkwater et al. 1997).

X-ray data for all Parkes quasars have been provided by Siebert et al. (1998). The fluxes are in the soft X-ray band 0.1–2.4 keV, and most were determined from the *ROSAT* All-Sky Survey and (for 49 sources) from archival pointed PSPC observations. Of the 323 sources in the Drinkwater et al. (1997) sample, 163 were detected in soft X-rays at the 3 σ level. For the remaining 160 sources, 2 σ upper limits to the counts were determined. We have used the total broadband fluxes as computed by Siebert et al. (1998) from the count rates, corrected for Galactic absorption only. Where available, we also use their estimates of the photon energy indices Γ (where $f_\nu \propto \nu^{1-\Gamma}$), determined from explicit power-law fits to spectral data or from hardness-ratio techniques (see § 4.1). In total, for our subsample of 119 Parkes quasars with contemporaneous photometry, 57 are detected in soft X-rays, and upper limits are known for the remaining 62.

3. OPTICAL EXTINCTION AND X-RAY ABSORPTION MODELING

As claimed by Webster et al. (1995), if the large spread in optical-to-NIR colors of Parkes quasars is due to reddening by dust, then it is expected that the reddest quasars may also be absorbed in soft X-rays. We test this hypothesis by making simple predictions involving optical-to–soft X-ray (α_{BX}) and NIR-to–soft X-ray (α_{KX}) continuum slopes. This section will briefly outline our assumptions and predictions using a simple gas-dust absorption model.

The degree of X-ray absorption by metal-enriched gas primarily depends on the total column density of gas in the line of sight. In the case of the Galactic ISM, where the metal abundance is typically $\lesssim 1\%$ relative to hydrogen by mass (Grevesse & Anders 1991), hydrogen and helium are responsible for almost all of the absorption at energies of $\lesssim 2$ keV. We predict the amount of X-ray absorption expected for a given optical-dust extinction measure by assuming, for simplicity, the range in Galactic gas-to-dust ratios derived empirically from Lyα absorption measurements in the Galaxy (Bohlin, Savage, & Drake 1978),

$$N(\mathrm{H\,I} + \mathrm{H_2})_{\mathrm{tot}} \simeq (5.8 \pm 2.5) \times 10^{21} \left(\frac{E_{B-V}}{\mathrm{mag}}\right) \mathrm{cm}^{-2} , \quad (1)$$

where E_{B-V} is the extinction (color excess) in $B-V$ color. This relation is also consistent with empirical estimates of the dust-to-gas ratio in the SMC and LMC by Bouchet et al. (1985) and Fitzpatrick (1985).

The effective X-ray optical depth, τ_{X}, defined such that the change in flux due to absorption is $\exp(-\tau_{\mathrm{X}})$, is given by

$$\tau_{\mathrm{X}} = \sigma_E N(\mathrm{H\,I} + \mathrm{H_2})_{\mathrm{tot}} , \quad (2)$$

where σ_E represents the effective absorption cross section per H atom at energy E, and $N(\mathrm{H\,I} + \mathrm{H_2})_{\mathrm{tot}}$ is defined by equation (1). We adopt cross sections for X-ray absorption as derived by Morrison & McCammon (1983) for a gas with Galactic ISM metal abundances. Typically, $\sigma_{1\,\mathrm{keV}} \simeq 2.42 \times 10^{-22}$ cm^2 and $\sigma_{2\,\mathrm{keV}} \simeq 4.30 \times 10^{-23}$ cm^2. Together with the ratio of total to selective extinction, $A_V/E_{B-V} \simeq 3.05 \pm 0.15$, as given by Whittet (1992), the optical depths at 1 and 2 keV from equation (2) can be written as

$$\tau_{1\,\mathrm{keV}} \simeq (0.46 \pm 0.19)\left(\frac{A_V}{\mathrm{mag}}\right) ,$$

$$\tau_{2\,\mathrm{keV}} \simeq (0.08 \pm 0.04)\left(\frac{A_V}{\mathrm{mag}}\right) . \quad (3)$$

As a simple estimate, if a source at redshift $z = 1$ (the median redshift of the Parkes quasar sample) suffers an intrinsic extinction $A_V = 2$ mag (a typical mean value for Parkes quasars; Masci 1997), then absorption by associated neutral gas would reduce the *observed* 1 keV flux by about a factor of $1/\exp[-\tau_{(1+z)1\,\mathrm{keV}}] \sim 1.2$. For comparison, assuming the generic $1/\lambda$ dust law, an intrinsic extinction of $A_V = 2$ mag will result in a decrease of the observed optical flux by a factor of >50. Thus, we see that the decrease in observed optical flux caused by dust extinction is generally larger than the corresponding decrease in soft X-ray flux caused by associated gas. Even for low-z sources, the discrepancy in flux reductions in these two regimes is about a factor of 5, and increases rapidly with z because of the energy dependence of σ_E. This property will become important when we examine the correlation involving optical-to–X-ray continuum slopes in § 3.1.

3.1. α_{BX} *and* α_{KX} *versus Optical Extinction*

Based on optical and X-ray spectral properties of Parkes quasars, both Webster et al. (1995) and Masci (1997) claimed that in most cases, the reddening is likely to be due to dust *intrinsic* to the quasars. Thus, for simplicity, the following analysis will assume all absorbing material to be located at the redshift of the quasar. We also assume that all predicted quantities discussed below (i.e., slopes and extinction measures) refer to the quasar rest frame.

If a source with some intrinsic (unabsorbed) optical-to–X-ray power-law slope, say α_{BX_i} (where $f_\nu \propto \nu^{-\alpha}$), suffers intrinsic absorption by dusty gas, then in its rest frame, the

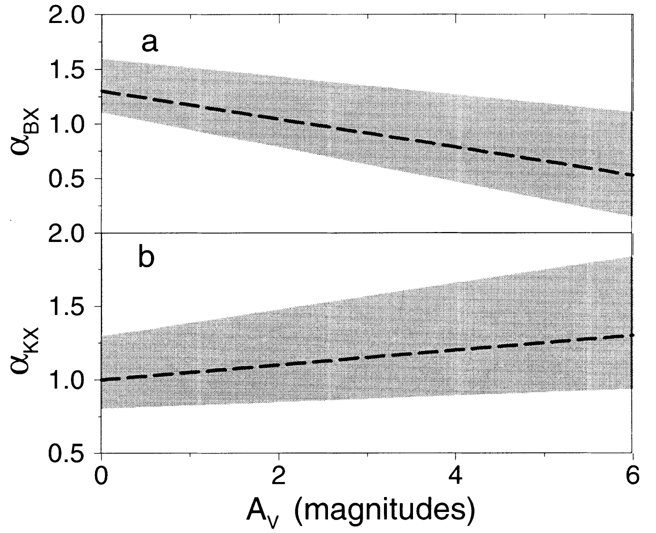

FIG. 1.—(*a*) Rest-frame B_j-to–1 keV power-law continuum slope ($f_\nu \propto \nu^{-\alpha}$), and (*b*) K_n-to–1 keV continuum slope as a function of optical extinction A_V predicted assuming the empirical ranges in Galactic dust-to-gas ratio, extinction measures, and intrinsic slopes as discussed in § 3. Dashed lines represent mean predictions.

resulting slope (α_{BX_0}) can be written in terms of extinction optical depths as follows:

$$\alpha_{BX_0} = \alpha_{BX_i} + \frac{\tau_X - \tau_B}{\ln(\nu_X/\nu_B)}. \tag{4}$$

We also consider the NIR-to–X-ray continuum slope (α_{KX_0}), so that analogously,

$$\alpha_{KX_0} = \alpha_{KX_i} + \frac{\tau_X - \tau_K}{\ln(\nu_X/\nu_K)}. \tag{5}$$

According to the available data, our analysis will assume the B_j bandpass ($\lambda = 475$ nm) for the optical and the K_n bandpass ($\lambda = 2.15$ μm) for the NIR. We consider the X-ray flux at 1 keV, so the optical depth τ_X in equations (4) and (5) is defined in terms of the optical extinction A_V by equation (3). Using the extinction coefficients $R_\lambda = A_\lambda/E_{B-V}$ from Savage & Mathis (1979) in the optical and from Whittet (1988) in the NIR for diffuse Galactic dust, we find

$$\tau_B \simeq (1.223 \pm 0.015)A_V\ ,$$

$$\tau_K \simeq (0.084 \pm 0.030)A_V. \tag{6}$$

By combining the above relations, we can see from equations (4) and (5) that for given intrinsic (unabsorbed) values of α_{BX_i} and α_{KX_i}, absorption by dusty gas will predict a specific correlation between optical extinction (A_V) and the corresponding absorbed continuum slopes.

To make some illustrative predictions applicable to radio quasars, the intrinsic slopes α_{BX_i} and α_{KX_i} need to be specified. As a working measure, we assume, for simplicity, that these slopes are those found for optically selected quasars. As argued by Masci (1997) and Francis et al. (1998), this choice is based on the claim that optically selected quasars are expected to be strongly biased against significant absorption by dust. This indeed is consistent with a number of studies that find a relatively small scatter in the optical-to–X-ray (1 keV) flux ratio of optically selected quasars (e.g., Kriss & Canizares 1985; Wilkes et al. 1994; La Franca et al. 1995). The distributions in this flux ratio indicate a mean value of $\langle\alpha_{BX_i}\rangle \sim 1.3$, with a dispersion $\sigma \sim 0.2$, that does not significantly differ between radio-loud and radio-quiet quasars (Wilkes & Elvis 1987; Green et al. 1995). This value is also consistent with that implied by a composite spectral energy distribution for radio-loud (optically selected) quasars derived by Elvis et al. (1994). Because of the absence of sufficient NIR data for optically selected samples, we adopt the K-to–1 keV continuum slope as indicated by this composite, where $\langle\alpha_{KX_i}\rangle \sim 1$, and assume a scatter similar to that found for α_{BX_i} in the studies above. From these studies, our predictions will assume the following ranges:

$$1.1 < \alpha_{BX_i} < 1.6\ ,$$

$$0.8 < \alpha_{KX_i} < 1.3\ . \tag{7}$$

The radio-selected Parkes quasars, for comparison, show a dispersion in α_{BX} that is almost 5 times greater (see § 4.2) than those of optically selected quasars (eq. [7]). Siebert et al. (1998) have shown that this is consistent with dust-gas absorption; however, the larger scatter could also include effects from any of the following: an additional X-ray emission component over and above that of the radio-quiet quasars, with a wide distribution of strengths and/or slopes; enhanced X-ray variability; or a strong angle dependence of the observed X-ray emission because of beaming. Although such effects can be important in some sources and can contribute to the scatter, our analysis here is purely concerned with the hypothesis that it is mostly due to variable amounts of absorption in the optical and X-ray bands.

Given the ranges in intrinsic slopes defined by equation (7) and the ranges defined by the uncertainties in the extinction measures $\tau_{1\,\mathrm{keV}}$ (eq. [3]), τ_B, and τ_K (eq. [6]), we show in Figure 1 the expected range spanned by α_{BX_0} and α_{KX_0} as a function of A_V. There appears to be a distinct behavior in each of these slopes with A_V, with an anticorrelation in α_{BX_0} and correlation in α_{KX_0}. As discussed in § 3 and as seen in equations (4) and (5), this is due to the amount of absorption expected in B_j and K_n relative to that at 1 keV. From the above discussion, we have typically $\tau_B/\tau_X \sim 2.7$ and $\tau_K/\tau_X \sim 0.2$, so that the correlation involving α_{KX_0} is purely a result of the fact that absorption causes a greater decrease in soft X-ray flux than that in the NIR. It is important to note that the trends of these correlations sensitively depend on the assumed dust-to-gas ratio (eq. [1]) and metallicity (i.e., the cross section σ_E in eq. [2]), which for simplicity were fixed to local ISM values. A variation in either of these quantities by at least a factor of 5 is likely to change the sign of the correlation.

The predictions in Figure 1 are represented by the following linear relations:

$$\alpha_{BX} = (1.3^{+0.3}_{-0.2}) - (0.13^{+0.03}_{-0.02}) \times A_V\ ,$$

$$\alpha_{KX} = (1.0^{+0.3}_{-0.2}) + (0.05^{+0.04}_{-0.03}) \times A_V\ . \tag{8}$$

Given the uncertainties, the slope of the α_{KX} versus A_V relation is insignificant; however, for typical Galactic ISM conditions, the crucial feature in Figure 1 is the opposite trend predicted in each of these slopes in the presence of absorption by dusty gas. This will provide a powerful diagnostic for testing the dust-reddening hypothesis for Parkes quasars.

4. COMPARISON WITH DATA

This section will compare the predictions of Figure 1 with estimates of the slopes involving the soft (0.1–2.4 keV) X-ray bandpass (α_{BX} and α_{KX}) derived from the available *ROSAT* data, and extinctions (A_V) derived from the observed optical reddening. To facilitate a direct comparison with the predictions of Figure 1, however, we first transform these quantities into the source rest frame.

4.1. *Spectral Slopes and Transforming to the Rest Frame*

Because of the frequency dependence of optical extinction and X-ray absorption, a similar dependence of these quantities on the redshift of the absorbing material in an observer's frame is expected. This implies that a plot similar to Figure 1 that uses observed quantities will also include a hidden and complicated dependence of the absorption on redshift. The added effects of changing spectral shape with source redshift (i.e., *K*-correction effects) will also introduce ambiguities. Thus, assuming that the absorbing material is intrinsic to the quasars, we will transform all observed quantities to the source rest frame. This will enable a direct and unambiguous comparison with the predictions of Figure 1.

We have used the total 0.1–2.4 keV X-ray fluxes as computed from the *ROSAT* count rates by Siebert et al. (1998), which were corrected for Galactic absorption only. The observed spectral indices [i.e., $\alpha_{BX}(\mathrm{obs}) \propto \log(f_X/f_B)$], were computed by first deriving monochromatic X-ray fluxes, f_X, at 1 keV. These were determined from the total broadband fluxes and available upper limits, assuming a power-law continuum ($f_\nu \propto \nu^{-\alpha_X}$) between 0.1 and 2.4 keV. Where available, we have used the photon indices Γ (where $\alpha_X \equiv \Gamma - 1$) determined from explicit power-law fits to spectral data and hardness ratio techniques by Siebert et al. (1998). These were available for 71 of the 119 sources. When an individual photon index was not available, the average photon index for radio-loud quasars, $\alpha_X = 1$ (e.g., Schartel et al. 1996), was used.

The rest-frame spectral indices, for example $\alpha_{BX}(\mathrm{rest})$, were determined by applying a simple *K*-correction that assumes a power-law in each of the optical and soft X-ray bands. If α_B and α_X are respectively the optical and X-ray power-law slopes, *z* is the source redshift, and $\alpha_{BX}(\mathrm{obs})$ is the observed optical-to–X-ray slope, then the corresponding value in the rest frame is given by

$$\alpha_{BX}(\mathrm{rest}) = \frac{(\alpha_B - \alpha_X)\log(1+z)}{\log(\nu_X/\nu_B)} + \alpha_{BX}(\mathrm{obs}) . \quad (9)$$

X-ray slopes, α_X, are taken from Siebert et al. (1998) as discussed above, and optical slopes, α_B, for each source were determined from the contemporaneous photometry, measured between the B_j and I ($\simeq 0.9\ \mu$m) passbands. In our determination of the NIR-to–X-ray slope $\alpha_{KX}(\mathrm{rest})$, the required NIR slopes, α_K, were determined between the B_j and K_n passbands.

Rest-frame optical extinctions A_V in each source were derived from the observed optical-to-NIR reddening, as defined by the contemporaneous colors $B_j - I$ and $B_j - K_n$, and assuming intrinsic (unabsorbed) colors as measured in optically selected quasars. As discussed in § 3.1, optically selected quasars are expected to be strongly biased against significant absorption by dust. This claim is consistent with their relatively small scatter in colors (e.g., Francis 1996) that lie predominately on the blue tail of the Parkes quasar color distribution. From quasi-simultaneous optical/NIR photometry by Francis (1996) of a subset of 37 quasars drawn from the optically selected LBQS sample of Hewett, Foltz, & Chaffee (1995), we find the following mean values and dispersions in intrinsic colors:

$$(B-K)_i = 2.3 \pm 0.5 ,$$
$$(B-I)_i = 0.9 \pm 0.4 . \quad (10)$$

We assume that these values represent the intrinsic (unabsorbed) colors of Parkes quasars. For our redshift range of interest, $0 \leq z \leq 3$, we also find that for these optically selected quasars, the colors show no significant dependence on redshift. We therefore assume the intrinsic colors (eq. [10]) to be independent of redshift *in an observer*'s frame.

Given a general dust extinction curve defined by $\xi(\lambda) \equiv A_\lambda/A_B$, the rest-frame optical extinction can be written in terms of an observed color, say $(B-K)_o$, and corresponding intrinsic color $(B-K)_i$, as

$$A_V = \left[\frac{\xi(\lambda_V)}{\xi(\lambda_B/1+z) - \xi(\lambda_K/1+z)}\right][(B-K)_o - (B-K)_i] , \quad (11)$$

where *z* is the source redshift. We have used the analytical fit for $\xi(\lambda)$ as derived by Pei (1992) for diffuse Galactic dust in the range 500 Å $\lesssim \lambda \lesssim 25\ \mu$m.

The rest-frame extinction A_V for each source was estimated by computing the average of the two extinction values obtained independently from the two observed colors $B_j - I$ and $B_j - K_n$. As shown in Figure 2, there is a tight correlation between these estimates for A_V, suggesting that each reddening indicator may equally provide a measure of the extinction. From the scatter about the line of equality, the values are consistent to within ±0.5 mag. This correlation suggests that the $B-K$ and $B-I$ colors of Parkes quasars vary with each other in such a way as to imply a characteristic spectral curvature from *B* to *K* that is

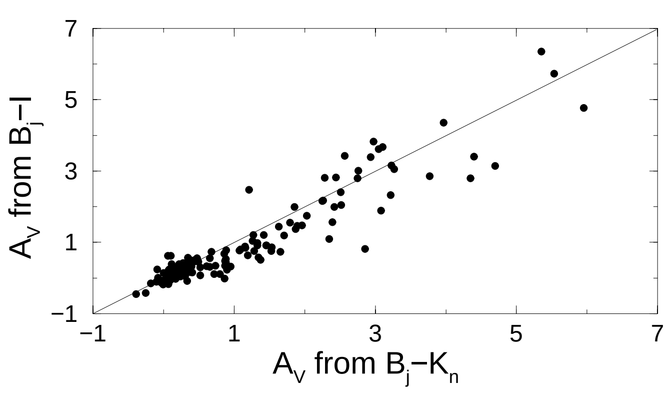

FIG. 2.—Rest-frame extinctions as determined from the observed $B_j - I$ colors vs. those determined from $B_j - K_n$. The diagonal line is the line of equality.

consistent with reddening by dust. This is unlikely to arise from an intrinsic relationships between these bandpasses in the source emission, such as a correlation between the I and K bands. Appropriate fine-tuning would be required to reproduce the result in Figure 2.

4.2. *Results and Model Comparisons*

Using the above formalism to convert the observed quantities in the source rest frame, Figure 3 shows the rest-frame spectral indices α_{BX} and α_{KX} as a function of the optical extinctions. The triangles represent 2 σ lower limits on these indices from the X-ray nondetections. In the lower left corners of each figure, we show two conservatively calculated error bars for both the A_V and the spectral indices. From the dispersions in our assumed intrinsic colors (eq. [10]) and scatter in Figure 2, we have typically $\sigma(A_V) \simeq 0.5$ mag. The spectral index error bar assumes a maximum error in the X-ray flux of 25% [i.e., $\sigma(\log f_X) = 0.25$; see Siebert et al. 1998] and an uncertainty in both the B_j and K_n bands of 0.2 mag (see § 2). Furthermore, following Siebert et al. (1998), we also included an uncertainty for possible variability in the nonsimultaneous X-ray and B_j (or K_n) measurements. This assumes a variability of $\sigma(B) = \sigma(K) = 0.3$ mag, typical for one of our quasars with a 20 yr rest-frame timescale between the optical and X-ray measurements (Hook et al. 1994). Combining these uncertainties, we have $\sigma(\alpha_{BX}) = \sigma(\alpha_{KX}) \simeq 0.15$.

The optical-to–X-ray slopes (Fig. 3*a*) and NIR-to–X-ray slopes (Fig. 3*b*) appear to be somewhat anticorrelated and correlated with A_V, respectively. We have formally computed the probabilities that the observed correlations are real by taking into account all lower limits on the spectral slopes and using the techniques of survival analysis. The correlation and regression analyses were performed using the ASURV package (Version 1.3; La Valley, Isobe, & Feigelson 1992), which is particularly designed for censored data, implementing the methods presented in Isobe, Feigelson, & Nelson (1986). For the correlation analysis, we applied the generalized Kendall's tau test, and for the regression analysis we used the parametric EM algorithm. For α_{BX} versus A_V (Fig. 3*a*), we find that the probability for *no* correlation is $P = 0.0006$, i.e., the hypothesis that these quantities are uncorrelated is rejected at the 99.94% confidence level. For α_{KX} versus A_V (Fig. 3*b*), we find $P < 0.0001$; this correlation is significant at the >99.99% confidence level. The solid lines in Figure 3 show our best regression fits to the data. Using ASURV, we have the following best regression line fits:

$$\alpha_{BX} = (1.41 \pm 0.02) - (0.08 \pm 0.02) \times A_V ,$$

$$\alpha_{KX} = (1.18 \pm 0.03) + (0.10 \pm 0.02) \times A_V . \qquad (12)$$

The observed anticorrelation and correlation involving α_{BX} and α_{KX}, respectively, appear broadly consistent with the predictions of our simple model in Figure 1. The predicted ranges in these slopes as a function of the optical extinction (taking account uncertainties in dust-to-gas ratios and intrinsic slopes; see § 3) are represented by the regions within the dashed curves in Figure 3. For $A_V \simeq 0$, we see that there is very good agreement between the observed slopes of Parkes quasars and our assumed range in intrinsic (unabsorbed) values (eq. [7]) from studies of optically selected quasars. The optical (and NIR)–to–soft X-ray continuum slopes of the bluest Parkes quasars therefore show relatively small scatter, similar to those of optically selected quasars, strengthening the claim that such sources are unbiased with respect to reddening by line-of-sight dust. The increased scatter in these slopes when all Parkes quasars are considered can then be attributed to dust extinction. In particular, the range in extinctions, $0 < A_V < 6$ mag, is consistent (within our conservative errors) with the maximum extinction $A_B \sim 4$ mag derived by Siebert et al. (1998) from the dispersion in optical-to–X-ray flux ratio alone.

Our results are also consistent with studies of the optical-to–soft X-ray continua of a large sample of medium to moderately hard X-ray–selected active galactic nuclei (AGNs) by Puchnarewicz et al. (1996). Their study suggests moderate absorption by dusty gas, with approximately Galactic dust-to-gas ratio and column densities of $N_{\rm H} < 5 \times 10^{21}$ cm^{-2}. Using the lower limit of $N_{\rm H}/E_{B-V} \simeq 3.3 \times 10^{21}$ cm^{-2} mag^{-1} from equation (1) and a Galactic extinction curve,

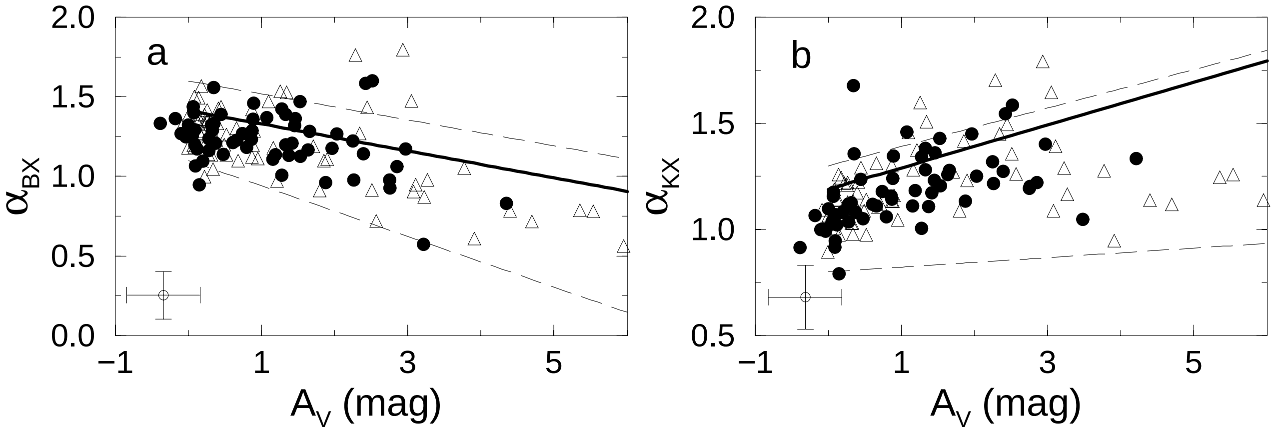

FIG. 3.—(*a*) Rest-frame B_j-to–1 keV continuum slope ($f_\nu \propto \nu^{-\alpha}$), and (*b*) K_n-to–1 keV continuum slope as a function of rest-frame optical extinction for Parkes quasars. Triangles show 2 σ lower limits from the X-ray nondetections. Errors in both A_V and slopes are represented by conservatively calculated error bars, shown in the lower left, as discussed in § 4.2. Dashed lines represent the extremities of the range predicted by our simple model (see Fig. 1). Solid lines show the best line regression fits.

this corresponds to $A_B \lesssim 6$ mag, entirely consistent with the range found in our sample of radio-selected quasars.

To summarize, we have found significant correlations between optical (and NIR)–to–soft X-ray continuum slope and optical extinction that are consistent with the predictions of a simple dust model. The results of Figure 3 imply that if the observed scatter in optical slopes of Parkes quasars is due to extinction by dust in their environs, then soft X-rays are absorbed at a level fully consistent with this hypothesis.

5. DISCUSSION

The anticorrelation involving α_{BX} and optical extinction (Fig. 3*a*) can be easily explained by gas-dust absorption, whereby optical flux is relatively more absorbed than that at 1 keV. This anticorrelation is qualitatively similar to that claimed by McDowell et al. (1989) for a sample of quasars that appeared to show a weak "big blue bump" feature relative to their NIR and soft X-ray emission. These authors, however, interpreted the trend as arising from an intrinsically varying blue-bump spectrum, and not extinction by dust. A changing blue luminosity may thus mimic a variation in optical extinction. It is therefore possible that the observed correlation in Figure 3*a* is spurious and due to a secondary trend, i.e., a dependence of both α_{BX} and A_V (or optical slope) on *B*-band luminosity. A direct investigation of the relationship between these quantities, however, shows that such an effect is unlikely to explain the observed trend. In addition, since the optical-UV flux in the blue-bump component also provides a source of photoionizing flux for emission-line regions, this model also predicts to first order a correlation between the equivalent widths of emission lines and the optical-UV continuum slope. However, our analysis of the emission-line equivalent widths for Parkes quasars (Masci 1997; Francis et al. 1998) strongly argues against this possibility. An intrinsically varying optical/UV continuum will also require the X-ray continuum to vary simultaneously in order to satisfy the correlation involving α_{KX} in Figure 3*b*. This, however, would be inconsistent with the trend in Figure 3*a*. Such a mechanism therefore requires physically unmotivated fine-tuning of the NIR, optical, and soft X-ray emission to explain the observed correlations.

The correlation involving α_{KX} (Fig. 3*b*) indicates that all of the optical-to–1 keV continuum flux appears absorbed relative to that in the NIR. It is encouraging to find that such a correlation is qualitatively similar to that claimed by Ledden & O'Dell (1983) between the radio-to–soft X-ray and radio-to-optical slopes for several optically reddened radio quasars. They concluded that absorption by associated gas and dust was the most likely explanation. Their statistics, however, were too low to support any firm conclusions.

The indirect confirmation for soft X-ray absorption from Figure 3 implies that the soft X-ray, optical, and possibly also the NIR continuum emission must traverse the same dust component. As suggested by previous studies attempting to explain the difference in soft X-ray spectral properties of radio-loud and radio-quiet quasars, a significant fraction of the soft X-ray flux in radio quasars is believed to arise from synchrotron self-Compton (SSC) emission associated with the radio-jet emission (e.g., Wilkes & Elvis 1987; Ciliegi et al. 1995). According to standard unified models for AGNs, the radio-jet emission may extend to distances $\gtrsim 10$ kpc from the central engine. Thus, if the soft X-rays are mostly SSC in origin, then the results of Figure 3 require the absorbing medium to extend on a scale similar to that of the radio emission. If, however, the absorbing medium were situated close to the central AGN, so that the SSC X-rays suffered minimal absorption (with effectively $\tau_X \approx 0$), then the predictions of Figure 3 will change drastically; a much steeper anticorrelation in Figure 3*a* and the opposite behavior (i.e., anticorrelation) in Figure 3*b* would be expected. More direct studies of X-ray absorption, preferably via high-quality spectral observations, are required to further explore this issue.

6. CONCLUSIONS

We have tested the dust-reddening hypothesis to explain the relatively large dispersion in optical-to-NIR colors of quasars in the Parkes sample of flat-spectrum radio sources by searching for associated absorption by gas at soft X-ray energies. We have used broadband (0.1–2.4 keV) *ROSAT* All-Sky Survey data and pointed PSPC observations provided by Siebert et al. (1998), as well as contemporaneous optical-NIR photometry available for 119 of the 323 sources in this sample.

A soft X-ray absorption signature was searched for indirectly by exploring the optical (and NIR)–to–X-ray continuum properties as a function of optical extinction, where specific strong correlations are expected under a simple gas-dust absorption model.

Our main conclusion is that significant correlations (at $>3\ \sigma$ confidence) are observed between the rest-frame optical (and NIR)–to–1 keV continuum slope and the optical extinction that are consistent with the predictions of a simple model. This model assumes the range in dust-to-gas ratios and metal abundances derived empirically from the Galactic ISM, the intrinsic (unabsorbed) slopes as observed in optically selected quasars, and, as suggested by previous studies, that all absorption is intrinsic to the quasars. Under these assumptions, we conclude that soft X-rays are absorbed at a level consistent with the range of extinctions observed, $0 < A_V < 6$ mag.

The dust-associated X-ray absorption is therefore consistent with physical conditions (e.g., the gas ionization state) found in the diffuse local ISM. No warm (ionized) absorption is required, since the data does not indicate excess X-ray absorption relative to that in the optical compared to the Galactic model predictions. This is contrary to numerous previous studies of the soft X-ray properties of AGNs. High-quality X-ray spectra that can detect heavy-metal absorption edges are, however, required to place stronger constraints on the physical properties. These data will also be necessary to provide "direct" estimates of the amount of X-ray absorption and to constrain the geometry of absorbing/emitting regions. Because of the faintness of many of the reddest sources, spectral data is currently unavailable, and will require the high signal-to-noise ratio and resolution capabilities of future X-ray missions such as the *Advanced X-Ray Astrophysics Facility* (*AXAF*) and *XMM*.

We are grateful to Siebert et al. for making available the *ROSAT* data (currently in press) and to Paul Francis for providing the unpublished contemporaneous photometry (to appear in Whiting et al. 1998, in preparation).

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