We present results of a study of 12 dust-reddened quasars with $0.4 < z < 2.21$ and reddenings in the range $0.15 < E(B-V) < 1.7$. We obtained ACIS-S X-ray spectra of these quasars, estimated the column densities toward them, and hence obtained the gas:dust ratios in the material obscuring the quasar. We detect almost all but one of the red quasars in the X-rays. Even though there is no obvious correlation between the X-ray–determined column densities of our sources and their optical color or reddening, all of the sources show absorbed X-ray spectra. When we correct the luminosity for absorption, they can be placed among luminous quasars; therefore, our objects belong to the group of high-luminosity analogs of the sources contributing to the X-ray background seen in deep X-ray observations. Such sources are also found in serendipitous shallow X-ray surveys. There is a hint that the mean spectral slope of the red quasar is higher than that of normal, unobscured quasars, which could be an indication for higher accretion rates and/or an evolutionary effect. We investigate the number density of these sources compared to type 2 AGNs based on the X-ray background and estimate how many moderate-luminosity red quasars may be found in deep X-ray fields.

Subject headings: galaxies: active — quasars: general — X-rays: galaxies

1. INTRODUCTION

For a long time, deciphering the nature of the X-ray background (XRB) was a key problem in astrophysics. In the last years with the launch of the new generation of X-ray telescopes, Chandra and XMM-Newton, it has been possible to resolve the XRB into discrete point sources in very deep X-ray images (e.g., Chandra Deep Field—South [Giacconi et al. 2001], Lockman Hole [Hasinger et al. 2001], and Chandra Deep Field—North [Brandt et al. 2001]). Most of these point source have harder spectra than known quasars. About 90% of the X-ray sources in these deep fields have an optical counterpart with $R < 24$ (Barger et al. 2003). Optical identification of these sources shows that while some objects are normal quasars, many are reddened quasars, narrow-line active galactic nuclei (AGNs), or low-redshift “normal” galaxies (Rosati et al. 2002). As a complement to the deep X-ray fields, studies of X-ray–weak quasars have yielded harder X-ray spectra and redder optical colors than normal quasars (Risaliti et al. 2003).

The discovery of large numbers of reddened quasars and narrow-line AGNs implies that a large amount of the accretion luminosity from material falling into black holes is hidden by dust (in the optical) and gas (in the soft X-ray). Although there is order-of-magnitude agreement between the amount of radiation produced by quasars over the lifetime of the universe and the mass accreted onto the black holes we see in the centers of galaxies today (Merritt & Ferrarese 2001), there is still discussion about the fraction of quasars that are obscured by dust. Population synthesis analysis of the hard XRB estimates that up to 90% of AGNs, whose evolution peaks at $z \approx 0.7$, are absorbed by dust (Giulietti et al. 2001; Ueda et al. 2003). This fraction of obscured quasars does not coincide with the quasar population we are used to seeing in the optical, in which the majority of quasars are blue, unabsorbed, and peak at larger redshifts. We might be missing a large number of dust-reddened quasars (Webster et al. 1995). It remains to be investigated what fraction of the quasar population we are missing in optical color-selected surveys, which are most effective at selecting quasars with blue optical colors.

In addition to the X-ray surveys, various techniques have been developed to find quasars that are redder than those typically found in optical quasars surveys. Radio-selected quasars overall seem to have redder colors (Francis et al. 2000; Gregg et al. 2002; White et al. 2003) than optically selected samples, although there is still some debate about how much of this redness can be produced by optical synchrotron emission in these powerful radio sources. In addition, broad absorption line (BAL) quasar samples have redder colors than typical quasars (Sprayberry & Foltz 1992; Reichard et al. 2003) and higher X-ray column densities (Gallagher et al. 2001), also suggesting that a large fraction of this population is missing from optically selected samples. Searches for red quasars have yielded a higher than normal quantity of lensed systems (Gregg et al. 2002; Lacy et al. 2002), whose discovery is aided by magnification bias, raising the possibility of large numbers of unmagnified obscured objects.

Although it seems clear that the reddening of quasars is caused by optical absorption by the warm dust obscuring the nuclear region, we do not yet know where this obscuration is taking place. The dust could be located in the host galaxy’s interstellar matter (ISM), but obscuration could also arise due to an accretion disk’s dusty regions. There is evidence that dust exists in the narrow-line region (NLR) of AGNs (Radomski et al. 2003), and even that as we move inward of the accretion disk, large dust grains could survive the radiation field in dense molecular clouds (Dopita et al. 2002). The location of the dust responsible for reddening is important in that we can compare it with the obscuring gas in the X-rays. Maiolino et al. (2001) speculate that AGN classification in the optical is different from that in the X-ray with $E(B-V)/N_H < 1$ lower than Galactic by a factor of $\sim 3$ up to $\sim 100$. We do not know what this ratio is for extremely absorbed quasars. Simple AGN models (e.g.,
Antonucci (1993) cannot explain this high dispersion, so the nuclear region of AGNs is apparently more complicated than usually assumed.

In this paper we present results of X-ray observations of 12 red quasars with *Chandra* and compare these results with other X-ray observation of red AGNs (Wilkes et al. 2002). Our principal aim is to investigate whether our optically selected X-rays are the high-luminosity analogs of the faint, red quasars found in the deep *Chandra* fields. Other shallow, serendipitous X-ray surveys have found cases of high-luminosity, obscured, or red type 2 quasars (Fiore et al. 2003), so our goal is that our objects fall into this category. We adopt a flat universe, \( H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1} \), and \( \Omega_\Lambda = 0.7 \) cosmology.

### 2. OBSERVATIONS AND DATA ANALYSIS

#### 2.1. Optical Selection Process

To find red quasars that could have been missed in optical surveys, we applied the following three criteria: (1) the object has to be a FIRST radio source (Becker et al. 1995), (2) it must be in the Two Micron All Sky Survey (2MASS) point-source catalog (Kleinmann 1992), and (3) it must have \( R - K \geq 4.8 \), based on comparison with the Palomar Observatory Sky Survey first (POSS I) or second generation (POSS II) images (McMahon & Irwin 1992). These criteria are similar to those of Glikman et al. (2004) but differ in one significant respect in that we also include objects that are detected on the POSS I as long as they satisfy our \( R - K \geq 4.8 \) criterion (using the POSS E magnitude as an approximation for \( R \)), while Glikman et al. did not. This results in the inclusion of several objects that are not present in the sample of Glikman et al. (2004).

The resulting candidate list included 20 objects detected on the POSS I plates, in addition to the 69 undetected objects in the Glikman et al. candidate list. Optical magnitudes for the candidates were obtained from the POSS II plates or from the Sloan Digital Sky Survey (SDSS) if they were in the area covered by data release 2 (Abazajian et al. 2004). Irregular host galaxies of or companions to our lower redshift red quasars can often be seen in the SDSS data, in agreement with studies of other red quasars (Hines et al. 2001).

Spectroscopy of our candidate quasars was carried out in the optical and near-infrared at various facilities. Objects with emission line widths >1000 km s\(^{-1}\) were classified as quasars. Twenty-eight of our 89 candidates turned out to be broad-line quasars with extremely red spectral energy distributions. The spectra of seven of our objects can be seen in Glikman et al. (2004), Gregg et al. (2002), and Lacy et al. (2002). The remaining five objects have similar spectra (red continuum, broad quasar lines, and no features associated with stellar light). Our requirement for detection of broad lines naturally excludes type 2 AGNs, and thus results in an expected X-ray column density of \( N_{\text{H}} < 10^{24} \text{ cm}^{-2} \).

The selection of red quasars based on \( R - K \) colors can, in principle, include objects that are red due to galaxy starlight; hence the need for high-quality spectra. However, since all the objects under discussion in this paper are high-luminosity quasars, it is not possible that the colors are dominated by starlight. Nonetheless, a quantitative discussion must go beyond colors to an actual determination of \( E(B - V) \). Where our spectra cover both \( H\alpha \) and \( H\beta \), the Balmer decrement can be used for this purpose. This is the case for 9 of the 12 objects. In calculating the Balmer decrements, we assumed an \( H\alpha/H\beta = 3.2 \) from the SDSS quasar composite (Vanden Berk et al. 2001). The errors from the Balmer decrement measurements are derived from propagating the line flux errors. Since the broad Balmer lines are presumed to arise only in quasars, the reddening derived from the Balmer decrement is independent of any starlight in the spectrum. In the three spectra that did not cover both \( H\alpha \) and \( H\beta \) (FTM 0906+4952, FTM 0915+2418, and FTM 1036+2828), we have fit the continuum slope following the technique described in Glikman et al. (2004). The spectra of these three quasars show no sign of starlight, e.g., from stellar absorption features (nor do the other nine spectra). Furthermore, the continuum estimates ranged up to the \( K \) band, where in the case of our luminous obscured quasars, starlight makes a negligible contribution to the spectrum, so the continuum slope should give a meaningful estimate of \( E(B - V) \).

It turns out that FTM 0906+4952 was a variable source that was especially bright when the infrared observations (2MASS) were being taken. Its reddening \( [E(B - V) = 0.15] \) is still somewhat redder than the mean SDSS quasar, but it does not compare to the extreme extinction shown by our other quasars. Nevertheless, we opted to keep FTM 0906+4952 in our sample for comparison reasons. The \( E(B - V) \) values are quoted in Table 1.

### Table 1

| Source      | R.A.     | Decl.     | \( z \) | Galactic \( N_H \) \((\times 10^{20} \text{ cm}^{-2})^2\) | \( K \) magnitude | \( R - K \) | \( E(B - V) \) | Observation Date | Exposure (s) |
|-------------|----------|-----------|--------|-------------------------------------------------|-------------------|------------|--------------|----------------|-------------|
| FTM 0134−0931 | 01 34 35.60 | −09 31 03.00 | 2.21   | 2.73                                            | 13.6              | 7.6        | 0.6 ± 0.2    | 2002 Aug 23      | 1078        |
| FTM 0729+3336 | 07 29 10.40 | +33 36 34.00 | 0.95   | 5.35                                            | 14.5              | 5.2        | 1.0 ± 0.2    | 2002 Feb 26      | 1899        |
| FTM 0738+2750 | 07 38 20.10 | +27 50 45.50 | 1.99   | 4.91                                            | 15.3              | 5.5        | 1.3 ± 0.4    | 2002 Apr 14      | 3998        |
| FTM 0830+3759 | 08 30 11.10 | +37 59 51.90 | 0.41   | 4.23                                            | 14.6              | 4.8        | 1.5 ± 0.2    | 2004 Jan 26      | 9203        |
| FTM 0841+3604 | 08 41 05.00 | +36 04 50.10 | 0.55   | 3.41                                            | 14.9              | 5.9        | 1.7 ± 0.3    | 2004 Feb 21      | 9318        |
| FTM 0904−0145 | 09 04 50.50 | −01 45 24.60 | 1.00   | 2.74                                            | 14.9              | 4.8        | 1.9 ± 0.5    | 2003 Nov 25      | 7515        |
| FTM 0906+4952 | 09 06 51.50 | +49 36 36.00 | 1.64   | 7.82                                            | 15.1              | 6.1        | 0.15 ± 0.3\(^b\) | 2004 Jun 01      | 3585        |
| FTM 0915+2418 | 09 15 01.70 | +24 18 12.20 | 0.34   | 3.24                                            | 13.8              | 5.5        | 0.5 ± 0.3\(^a\) | 2003 Nov 27      | 3205        |
| FTM 1004+1229 | 10 04 24.90 | +12 29 22.40 | 2.65   | 5.59                                            | 14.5              | 6.3        | 1.2 ± 0.3    | 2004 Jun 07      | 17666       |
| FTM 1012+2825 | 10 12 30.50 | +28 25 27.20 | 0.94   | 2.57                                            | 15.2              | 5.2        | 1.8 ± 0.3    | 2002 Apr 25      | 3309        |
| FTM 1022+1929 | 10 22 29.40 | +19 29 39.00 | 0.41   | 2.34                                            | 15.2              | 4.4        | 0.5 ± 0.3    | 2004 Mar 28      | 6607        |
| FTM 1036+2828 | 10 36 33.50 | +28 28 21.60 | 1.76   | 2.08                                            | 15.3              | 4.9        | 0.5 ± 0.3\(^b\) | 2002 May 07      | 4136        |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. We use FIRST coordinates, which are in J2000 epoch.

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\(^{a}\) The Galactic absorption was obtained from Skyview’s \( N_H \) survey, based on Dickey & Lockman (1990).

\(^{b}\) These objects have continuum reddening estimates. For the remaining objects, the Balmer decrement was used to derive \( E(B - V) \).
Our sample for study with Chandra was restricted to $z > 0.4$ to ensure that it contained moderate- to high-luminosity quasars (the least-well-studied obscured AGNs population in the X-ray).

Also, to ensure that the red colors of our quasars were not caused by an optical synchrotron component (Whiting et al. 2001), we included only objects with faint radio fluxes (<20 mJy at 1.4 GHz) or objects with higher radio fluxes but that show clear Balmer decrements in their optical/near-infrared spectra. Among the quasars chosen are FTM 0134 (a gravitational lens) and FTM 0738 (an upper limit).

For the observations, the Advanced CCD Imaging Spectrometer (ACIS-S) backside-illuminated CCD (S3) with a $\alpha$ subarray was used (faint mode). Table 1 shows the journal of observation of our quasars.

The ACIS images were analyzed with the CIAO package, version 3.0.1. We used the detection algorithm sedetect; all but one source were detected at the positions predicted by the optical data. The nondetected source (FTM 0738+2750) displays two very hard photons at the optical position of the quasar. FTM 1022+1929 shows two peaks; it might be a missed gravitational lens, although the detection algorithm classified it as one source.

Table 2 shows the X-ray properties of our sources. In our convention 0.2–10.0 keV represents the broad, 0.2–2.0 keV the soft, and 2.0–10.0 keV the hard energy range. The hardness ratio (HR) is defined as $HR = (H - S)/(H + S)$, where $S$ is the number of photons in the soft band and $H$ is the number of photons in the hard band. Table 3 shows our deduced HRs in column (2). As these are not the bands typically used in Chandra.

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### Table 2

**X-Ray Parameters**

| Source       | R.A.       | Decl.        | X-Ray Counts | $f_X$ (BROAD) | $L_X$ (0.5–10.0 keV) |
|--------------|------------|--------------|--------------|---------------|---------------------|
|              |            |              | Total        | Soft          | Hard                |
| FTM 0134     | 01 34 35.66| −09 31 02.8  | 95 ± 12      | 52 ± 9        | 40 ± 8              | 7.57 × 10^{-11}      |
|              |            |              |              |               |                     | 1.10 × 10^{36}       |
| FTM 0729     | 07 29 10.33| +33 36 33.9  | 6.0 ± 3.7    | 0             | 5.0 ± 3.6           | 3.04 × 10^{-14}      |
|              |            |              |              |               |                     | 1.01 × 10^{34}       |
| FTM 0738     | Not detected| Not detected |              |               |                     | 5 × 10^{-15}         |
| FTM 0830     | 08 30 11.5 | +37 59 51.8  | 790 ± 30     | 400 ± 20      | 390 ± 20            | 7.90 × 10^{-13}      |
|              |            |              |              |               |                     | 3.42 × 10^{34}       |
| FTM 0841     | 08 41 04.98| +36 04 50.2  | 5.4 ± 3.8    | 3.0 ± 3.0     | 3.0 ± 3.0           | 5.17 × 10^{-15}      |
|              |            |              |              |               |                     | 4.52 × 10^{33}       |
| FTM 0904     | 09 04 50.53| −01 45 24.7  | 6.0 ± 3.7    | 3.0 ± 3.1     | 3.0 ± 3.1           | 6.89 × 10^{-15}      |
|              |            |              |              |               |                     | 2.61 × 10^{34}       |
| FTM 0906     | 09 06 51.53| −49 52 35.8  | 40 ± 8       | 26 ± 7        | 13 ± 5              | 6.12 × 10^{-14}      |
|              |            |              |              |               |                     | 7.35 × 10^{34}       |
| FTM 0915     | 09 15 01.72| +24 18 11.9  | 68 ± 10      | 23 ± 7        | 48 ± 8              | 1.92 × 10^{-13}      |
|              |            |              |              |               |                     | 4.72 × 10^{34}       |
| FTM 1004     | 10 04 24.88| +12 29 22.4  | 41 ± 9       | 22 ± 7        | 26 ± 10             | 6.74 × 10^{-14}      |
|              |            |              |              |               |                     | 2.31 × 10^{34}       |
| FTM 1012     | 10 12 30.48| +28 25 26.0  | 10 ± 5       | 5.4 ± 3.8     | 5.0 ± 3.6           | 2.69 × 10^{-14}      |
|              |            |              |              |               |                     | 8.73 × 10^{34}       |
| FTM 1022     | 10 22 29.3 | +19 29 39.1  | 11 ± 5       | 3.9 ± 3.7     | 7.4 ± 4.2           | 1.45 × 10^{-14}      |
|              |            |              |              |               |                     | 6.28 × 10^{34}       |
| FTM 1036     | 10 36 33.55| +28 28 21.2  | 48 ± 8       | 34 ± 7        | 19 ± 6             | 9.70 × 10^{-14}      |
|              |            |              |              |               |                     | 1.36 × 10^{35}       |

**Notes.—** Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. The flux given for the nondetected source is the background flux and is considered an upper limit. Coordinates listed are in J2000 epoch and are for the Chandra X-ray. Units of $f_X$ are ergs cm$^{-2}$ s$^{-1}$ and units of $L_X$ are ergs s$^{-1}$.

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### Table 3

**Hardness Ratios**

| Source       | HR 0.2–2.0 and 2.0–10.0 keV | HR 0.5–2.0 and 2.0–7.0 keV | Corrected HR 0.4–4.0 and 4.0–20.0 keV |
|--------------|----------------------------|---------------------------|--------------------------------------|
|              | Observed Frame (2)         | Observed Frame (3)        | Rest Frame (4)                       |
| FTM 0134-0931| −0.12 ± 0.13              | −0.06 ± 0.13              | +0.54 ± 0.12                        |
| FTM 0729+3336| +1.00 ± 0.72              | +1.00 ± 0.72              | +1.00 ± 0.40                        |
| FTM 0738+2750| ...                       | ...                       | ...                                  |
| FTM 0830+3759| −0.02 ± 0.04              | −0.02 ± 0.04              | −0.34 ± 0.04                        |
| FTM 0841+3604| +0.00 ± 0.71              | +0.00 ± 0.71              | +0.00 ± 0.71                        |
| FTM 0904+0145| +0.00 ± 0.73              | +0.00 ± 0.73              | +0.00 ± 0.73                        |
| FTM 0906+4952| −0.34 ± 0.20              | −0.34 ± 0.20              | −0.16 ± 0.21                        |
| FTM 0915+2418| +0.36 ± 0.15              | +0.36 ± 0.15              | +0.26 ± 0.15                        |
| FTM 1004+1229| +0.10 ± 0.23              | +0.10 ± 0.23              | +0.55 ± 0.26                        |
| FTM 1012+2825| −0.04 ± 0.50              | −0.04 ± 0.50              | −0.04 ± 0.50                        |
| FTM 1022+1929| +0.32 ± 0.50              | +0.34 ± 0.45              | −0.21 ± 0.43                        |
| FTM 1036+2828| −0.27 ± 0.17              | −0.30 ± 0.17              | −0.02 ± 0.18                        |

**Notes.—** The first HR uses 0.2–2.0 keV as the soft and 2.0–10.0 keV as the hard band to obtain the most photons in each band. The second HR is the HR typically used in Chandra surveys, 0.5–2.0 keV for the soft and 2.0–7.0 keV for the hard band. The last HR is corrected for redshift, so we used the bands of the first HR at $z = 1$, or 0.4–4.0 keV for the soft and 4.0–20.0 keV for the hard band in the quasar rest frame.
surveys, we also show the HR with 0.5–2.0 keV in the soft band and 2.0–7.0 keV in the hard band in column (3) of Table 3. As expected, the color or hardness ratio of FTM 0906+4952 (the variable source) in the X-ray was the softest in our sample.

We then extracted the source and background pulse-height amplitude (PHA) spectra for the X-ray sources with more than 40 counts detected. For the source a 5σ circle region was used, and for the background an (30′′ × 15′′) annulus region was used. The response function (RMF) was then extracted, corresponding to the region of the chip where the source was located. The spectral analysis of the X-ray sources was carried out with XSPEC version 11.2.0, as part of the Xanadu package, obtainable at HEASARC.4 An absorbed power-law model at the quasar redshift was fitted to the spectra. We used the photoelectric, redshift-corrected absorption model, with Wisconsin cross sections (Morrison & McCammon 1983), in XSPEC zwabs. These fits yielded us the values of the spectral slope (Γ) and column density (N_H) in the rest frame of the quasar (see Table 4). The resulting spectra are shown in Figure 1.

3. RESULTS

One of the remarkable, if not surprising, results we find is that all of the red quasars are absorbed to some degree in the X-rays, as they have harder X-ray colors than typical quasars. Most of our sources have a low S/N; therefore, we cannot get accurate spectral slopes and column densities. However, from the measured HRs alone, we can extract useful information for the faint sources. Our sample has a mean HR of 0.08 ± 0.11 (observed frame). The mean HR changes very little (0.09 ± 0.10) when we calculate it with the bands normally used in Chandra deep fields: soft = 0.5–2.0 keV, and hard = 2.0–7.0 keV (see Table 3). This value is higher than expected in nonbiased X-ray surveys, in which the median HR of a typical quasar lies more around ~0.5 (Rosati et al. 2002). We then corrected the HR for redshift. For absorbed sources the absorption cutoff moves to lower energies when the object is at high redshift, so the corrected HR tends to be softer at higher redshift. We chose a HR at z = 1, that is the 0.4–4.0 and 4.0–20.0 keV bands in the rest frame; the values are quoted in column (4) of Table 3. The mean for the corrected HR is 0.15 ± 0.10.

Figure 2 shows the distribution of redshift-corrected hardness ratios versus reddening. There is no clear correlation between the reddening and the hardness ratio of our sample.

Table 4

| Source          | \( N_H \) \((\times 10^{22} \text{ cm}^{-2})\) | \( \Gamma \) | Corrected \( L_X \) \((\text{ergs s}^{-1})\) \((0.5–10 \text{ keV Rest Frame})\) |
|-----------------|--------------------------------------------|--------------|-------------------------------------------|
| FTM 0134–0931   | 5.9 ± 2.8                                  | 1.8 ± 0.5    | 2.4 × 10^{46}                            |
| FTM 0134–0931   | 1.4 ± 0.6                                  | 1.8 ± 0.5    | 2.4 × 10^{46}                            |
| FTM 0830+3759   | 2.7 ± 0.2                                  | 2.9 ± 0.1    | 2.1 × 10^{45}                            |
| FTM 0906+4952   | 0.6 ± 0.9                                  | 1.5 ± 1.0    | 6.3 × 10^{44}                            |
| FTM 0915+2418   | 6.7 ± 4.3                                  | 2.5 ± 1.2    | 2.3 × 10^{45}                            |
| FTM 1004+1229   | 28 ± 25                                    | 2.3 ± 1.3    | 8.6 × 10^{45}                            |
| FTM 1036+2828   | 3.8 ± 3.4                                  | 2.3 ± 1.3    | 3.5 × 10^{45}                            |

Notes.—The luminosity is corrected for absorption and is given in rest-frame band 0.5–10 keV. For FTM 0906+4952 the luminosity actually decreases, because it has a flatter spectral slope than the assumed \( \Gamma = 2 \) in Table 2 and a relatively small absorption.

* Absorption at quasar redshift.

* Absorption at lens redshift.

Shown are 1 σ error bars on the HR, to get an idea of how low the S/N is. We have calculated quasar models with \( \Gamma = 2 \) and different gas:dust ratios. The solid line represents the Galactic gas:dust model \( [E(B-V)]/N_H = 6 \times 10^{21} \text{ cm}^{-2} \); the short-dashed line represents a model with 20 times Galactic gas : dust ratio, and the long-dashed line is a model with a gas : dust ratio of 100 times Galactic value.

Wilkes’s X-ray observations of a sample of 26 low-redshift AGNs (Wilkes et al. 2002) has a mean observed-frame HR of +0.14 ± 0.05, slightly higher than our sample. This higher HR is expected for lower redshift models, as the absorption cutoff is at higher energies. Again, for the few objects of Wilkes’s sample for which we could obtain X-ray spectral information, no obvious correlation between reddening and column density is found.

Nevertheless, our redshift-corrected HRs all lie around the regime where the column density tends to be around a few times 10^{22} cm^{-2}, so there should be obscuration in the quasars, although not the obscuration we typically associate with Seyfert 2 galaxies, where the typical column density lies around 10^{24} cm^{-2}. Column densities around 10^{22} cm^{-2} are directly verified in those cases having large enough counts to allow a proper spectral fit (Table 4), which seems to indicate that the absorbed power-law model we chose for the spectra is the correct one.

In addition, the fact that our points all have column densities larger than expected from the dust reddening (assuming a Galactic gas:dust ratio) confirms the results of Maiolino et al. (2001), who claim that the \( E(B-V)/N_H \) ratio is lower than Galactic by a factor of ~3–100 and that this is due to the circumnuclear region being dominated by large dust grains. For the largest redenings in Figure 2, however, the gas:dust ratio seems to approach Galactic value, in contradiction to Maiolino et al. (2001). One possible explanation for this is that the ISM of the host galaxy itself could be doing the obscuration for the extremely reddened objects.

For the quasars, when we could extract a spectrum, we corrected for the absorption given by our models deduced with XSPEC (Table 4). The corrected luminosity value for FTM 0134–0931 is likely to be wrong, as there is luminosity enhancement due to the gravitational lens, but the correction for the other quasars places them among the high section of the quasars luminosity function. Our quasars therefore should represent only the tip of the red quasar iceberg; at lower X-ray luminosities we should find higher numbers of them, which is in agreement with the results from the X-ray deep fields. Luminosity correction for the AGNs in Wilkes’s sample do not show such high luminosities, a logical finding, as they are at lower

4 See http://xspec.gsfc.nasa.gov.
Fig. 1.—X-ray spectra of the sources with more than 40 counts. Shown are the counts with at least 2 $\sigma$ significance. They were fitted with an absorbed power-law model. For FTM 0134–0931 we show the model with the lens as the absorber. For FTM 0830+3759 we show 4 $\sigma$ significance, since the spectrum has over 700 counts. This spectrum also has a broadened Fe K line added to it. It also shows other absorption and emission features, which cannot be resolved.
redshifts. The fact that we do not see these exceedingly large luminosities at low redshift in the Wilkes sample rules out the possibility that all highly reddened quasars are highly luminous. As our sample is highly luminous and at higher redshift, we are obviously missing an even larger, as yet undiscovered, population of quasars at lower luminosity, in agreement with findings from White et al. (2003).

It has often been put forward that the higher than normal steepness of the X-ray spectrum in BAL quasars and narrow-line Seyfert 1 galaxies (NLS1) is a signature of a high accretion rate (Mathur 2000; Boller et al. 1996). Becker et al. (2000) speculate that the popular notion that all BAL quasars are normal quasars seen edge-on is wrong and that the nature of BALs could be more of an evolutionary effect. If BAL quasars and NLS1s were to represent an early phase in quasar evolution, the steeper than normal spectrum we find in red quasars could also represent an evolutionary phase in the lifetime of a quasar. To investigate this possibility, we need a bright enough sample to find the intrinsic power law, as the quasars themselves are obscured. We have to probe this hypothesis for the quasars that lie on the high end of the intrinsic X-ray luminosity function.

The quasars with spectral information also present a somewhat steeper spectral slope than normal quasars. The unweighted mean $\Gamma$ for our sample is $2.2 \pm 0.4$. We use the unweighted mean, because otherwise we would be dominated by FTM 0830+3759, which has very small errors (weighted mean $\mu' = 2.8 \pm 0.1$). The fact that our red quasars are radio selected actually contradicts broadband studies of quasars that have found that radio-loud quasars tend to have flatter spectra in the X-ray ($\Gamma \approx 1.6$) than radio-quiet quasars ($\Gamma \approx 1.8$), although there is a large scatter for both types (Elvis et al. 1994). Usually Seyfert 1 galaxies tend to have $\Gamma \approx 1.8$–1.9 for energies between 0.2–10.0 keV (Walter & Fink 1993), so our mean is slightly above the expected spectral index. To make sure that we are getting the correct spectral slopes, we also fit a simple power law to the high-energy region in the spectra, where absorption is not a factor. These new spectral slopes do not vary from the other ones significantly and are well within the errors. Their mean is $2.1 \pm 0.5$. The errors are larger, since we are fitting even fewer counts. The fact that the slopes from the fit to the high-energy portion of the spectra are similar to those obtained from modeling of the whole spectrum suggests that our fitting is reliable, and that the higher spectral slopes we obtain are not an artifact of the absorbed power law model we chose. There is only a marginal evolution of the spectral index with redshift (Fig. 3). The spectral index flattens somewhat at higher redshift, because the reflection hump in the rest-frame range of 10–40 keV moves into the Chandra band at high redshift (Schartel et al. 1996).

Wilkes’s red AGNs also have statistically larger than usual spectral index, with a weighted mean of $2.3 \pm 0.2$ and an unweighted mean of $2.2 \pm 0.2$. The fact that the spectral indices for red quasars are larger than expected could be an indicator of these objects having larger accretion rates. Just like NLS1 galaxies or BAL quasars, the red quasar phenomenon could be an evolutionary stage in the quasar lifetime. The quasar would be obscured, as it has just ignited, and the dust is still settling in. All of the deduced values of $\Gamma$ for the red quasars are still in a normal range for Seyfert 1 galaxies within the errors, but overall the values are higher.

We now comment briefly on our two brightest sources, for which we could get the most spectral information.

3.1. FTM 0134–0931

This FIRST-2MASS object is extremely red ($R - K = 7.61$). It has been identified as a lensed quasar, showing absorption lines from the lensing galaxy in the optical spectrum (Gregg et al. 2002; Winn et al. 2002). The quasar lies at a redshift of $z = 2.21$, while the lensing galaxy is at $z = 0.76$. Even with such a short exposure time of 1.1 ks, the quasar had around 95 detection counts, which was enough to get spectral information. When we analyze the X-ray spectrum, neither an absorbed power-law fit at the redshift of the quasar nor one at the redshift of the lens seems to yield a satisfying fit. Nevertheless, the inferred column density
is strongly dependent on which system is doing the absorption $(N_H = 1.378 \times 10^{22} \text{ cm}^{-2}$ if the lens is absorbing; $N_H = 5.925 \times 10^{22} \text{ cm}^{-2}$ for absorption within the quasar).

One fact that complicates this analysis is that in the radio, we see a lensing geometry of five radio components; it seems that the lensing galaxy itself has a radio counterpart (Gregg et al. 2002). It might well be that the lensing galaxy is an AGN, accounting for a soft component in the X-rays. So far, no simple model has been able to account for this object in any wavelength range. Further X-ray spectroscopy with a longer exposure time could support the claim that the lensing galaxy is an AGN, if we do see hints for two power laws.

3.2. FTM 0830+3759

When FTM 0830+3759 was observed for approximately 9.2 ks, it showed a bright X-ray source with close to 800 counts. We have fitted an absorbed power law to FTM 0830+3759, which is absorbed in the soft X-rays (see Table 2). Note that, although this is a fairly bright X-ray quasar, we are able to fit the broadened iron Kα line, which you can see from the “hump” at around 4.5 keV in the upper-right panel of Figure 1. More features are clearly visible in the spectrum, although it is not clear if they are emission lines that become visible as the power law gets absorbed or if they are absorption lines associated with the warm absorbing gas.

In FTM 0830+3759, we are probably looking almost directly into the accretion disk, as we see the Fe Kα emission line (6.4 keV) with a 4 σ significance. Fits with XSPEC estimate its width to about 0.6 keV $(4 \times 10^4 \text{ km s}^{-1})$, which should only be possible at the extreme relativistic areas of the accretion disk (about 20 Schwarzschild radii). This fit should however be taken with a grain of salt, as it has big errors (0.3 keV). Better resolution will tell us what the conditions are near the black hole. It is interesting to note that if we correct the luminosity for the obscuration obtained with the spectral fit $(2.661 \times 10^{22} \text{ cm}^{-2})$, it places FTM 0830+3759 among luminous X-ray quasars in the sky $(L_X = 3.89 \times 10^{45} \text{ ergs s}^{-1})$. At such luminosities, the accretion disk could be completely ionized and would not produce the Fe K reflection component, which comes from a cooler disk (“X-ray Baldwin effect”; Nandra et al. 1995).

FTM 0830+3759 also has the steepest spectrum of all our red quasars, a hint for a large accretion rate. Note from the spectrum that the quasar probably has a soft excess, which is not included in the model. If we ignore the spectrum to an energy of approximately 0.85 keV, the statistics get significantly better (almost all $\chi < 2$), and we obtain more absorption and a steeper spectrum $(N_H = 3.09 \times 10^{22}$ and $\Gamma = 3.1$). This further supports our view that FTM 0830+3759 is a young quasar with a high accretion rate, an obscured analog to NLS1s (Mathur et al. 2001).

4. DISCUSSION

Even though all of our quasars show absorption in the X-rays, it is not enough to classify them as type 2 AGNs in the X-ray $(N_H > 10^{24} \text{ cm}^{-2})$. This fact is interesting, because it is believed that highly obscured objects, preferably Seyfert 2 galaxies at low redshifts, make up the hard XRB, which peaks at around 40 keV. But so far, more quasars with only moderate obscuration have been found in faint X-ray surveys than have type 2 quasars. Highly obscured quasars have been found in X-ray surveys (Norman et al. 2002), but not in the numbers necessary to account for the hard XRB (Fabian et al. 2002). It is still not certain what fraction of Compton-thick AGNs make up the XRB. In that context, we do not know what fraction of the XRB is made up by red quasars, but our objects appear to be the high-luminosity equivalents of the bulk of faint X-ray sources, which are not Compton thick.

In recent times, in the Chandra deep fields, a new population of sources has been discovered that have extreme X-ray/optical ratios, the so-called EXOs (Koekemoer et al. 2004). In that sense, our red quasars are the high-luminosity equivalent of these objects, having high X-ray and IR flux compared to the optical. The higher accretion rates suggested by the spectral indices in our objects could be a hint that they are the same population. The EXO population seems to have atypically higher accretion rates than implied by the $M_{BH} - \sigma$ when comparing their X-ray flux to the K-band magnitude of their hosts. The high accretion rates are indications that our objects and EXOs are still young, with the dust just settling in. This may be a common phenomenon; nevertheless, it still remains to be seen what fraction of objects in deep X-ray surveys belong to the population of EXOs.

Deeper optical surveys are needed to detect red quasars, beyond the highly luminous obscured ones. By obtaining the fraction of obscured quasars at a certain redshift, we can then tell if the missing population of the hard XRB is made up primarily of type 1 obscured AGNs or Compton-thick type 2 AGNs. To this day, this has proven difficult because selection criteria, such as color-color properties, to find red quasars are not yet established. For example, light from the host galaxies will dominate over the quasar light at blue wavelength. Optical surveys also are magnitude limited, so it will be a difficult task to find the bulk of obscured quasars (White et al. 2003). Another fact that complicates this analysis is that we have found that the red color in quasars is not closely correlated to the column density of X-ray–absorbing material, which makes it difficult to speculate on X-ray properties from IR/optical data alone. Using the Spitzer Space Telescope (Werner et al. 2004), we might be able to discern the true fraction of obscured to unobscured AGNs, due to the fact that the mid-infrared (MIR) emission regions of AGNs are less obscured, and we can easily distinguish the galaxies from AGNs from the MIR spectral energy distributions (SEDs) alone (Lacy et al. 2004).

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