RADIO-QUIET RED QUASARS

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ABSTRACT

We have performed a successful targeted search for a population of red radio-quiet, and probably absorbed, quasars. Radio-quiet, optically-red ROSAT PSPC X-ray sources brighter than $1 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ were searched for red ($O-E > 2.0$, $O \leq 20$) counterparts in the APM catalog of Palomar Sky Survey objects. Of 45 objects for which we obtained adequate follow-up optical spectroscopy, we have found 7 red quasars, 5 with $\alpha_{opt} < -2$. Their redshifts range from 0.06 to 0.31, and their luminosities are moderate, lying on the Seyfert/Quasar boundary. These red quasars strengthen the case for a radio-quiet population that is the counterpart of the radio-loud red quasars found by Smith and Spinrad (1980), and Webster et al. (1995). Unidentified, fainter, sources could increase the fraction of red quasars by up to a factor 7.

For the red quasars found here, the $H\alpha/H\beta$ ratios, optical slope and X-ray colors all indicate that they are absorbed by $A_V \sim 2$, rather than having intrinsically red spectra. This amount of obscuration seems to hide $\sim 1-7\%$ of quasars at a given observed flux, or $\sim 3-20\%$ when their fluxes are corrected to their intrinsic values. This size of population is consistent with earlier limits, with predicted values from Comastri et al. (1995), and is comparable to the rate found among radio-loud quasars.

A large population of more heavily absorbed ($A_V = 5$), fainter, quasars equal in size to the blue population could exist, without violating existing upper limits, in accord with the Comastri et al. (1995) predictions.

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1. Introduction

Quasars are the canonical “ultraviolet excess” objects (Sandage 1965). Yet red quasars have been found in radio-selected samples by Smith and Spinrad (1980) and Webster et al. (1995). Webster et al. (1995) proposed that a large fraction, perhaps 80%, of radio-loud quasars might have been hidden as red objects. Moreover, the currently favored explanations for the cosmic X-ray background invoke a population of heavily obscured active galactic nuclei (AGNs) 5 times more common than the unobscured population (Comastri et al., 1995). If the small number of known red quasars really are the ‘tip of the iceberg’ of a large, even dominant, quasar population then the consequences would be interesting: the overall AGN population - and so the massive black hole population - may be five times larger than had been thought; obscured quasars would be a long-lived evolutionary phase (c.f. Sanders et al., 1988), or all quasars may be hidden along 80% of possible lines of sight; and red quasars may contribute importantly to the cosmic X-ray background. The Webster et al. conclusion is widely disputed. Boyle & di Matteo (1995), Stickel et al. (1996) and Benn et al., (1998) all argue that any missing population must be smaller, and perhaps insignificant, while Gunn & Shanks (1998) disagree. Here we present an X-ray based survey targetted explicitly at red AGN, to find radio-quiet red quasars.

Radio-loud red quasars are relatively easy to find, since the radio emission is unaffected by absorbing gas or dust and, in low frequency surveys, usually comes from the large radio lobes that lie well outside any obscuring material in the host galaxy. An explicit, albeit small-scale, search for radio- and X-ray-loud but optically-quiet quasars, which should include reddened quasars was, however not successful (Kollgaard et al., 1995).

Radio-quiet red quasars are much harder to find, although they might be expected to be much more common. In the normal unreddened population radio-quiet quasars outnumber radio-loud quasars 10 to one (e.g. ‘EMSS’ Stocke et al. 1991; ‘PG’ Kellerman et al., 1989). However, most optical quasar surveys are actively biased against finding red quasars. Since these surveys primarily search for UV bright objects (e.g. ‘Markarian’, Lipovetsky, Markarian & Stepanian 1987; ‘PG’, Schmidt and Green 1981; ‘LBQS’, Hewett et al. 1995; ‘HS’ Engels et al., 1998) they are blind to red objects. As a result optical bounds on how large a population of radio-quiet red quasars might exist are weak.

X-ray selection provides a way of selecting red quasars efficiently: hard X-rays (2-10 keV) penetrate even 10s of magnitudes of optical extinction with minimal absorption. Even the lower energy band of ROSAT (0.5-2.5 keV) is not strongly affected by optical extinction of up to ∼2 magnitudes. Astrophysics might be against us since, although blue quasars are overwhelmingly X-ray loud (Avni and Tananbaum 1986), red ones might be intrinsically X-ray faint. Fortunately though, radio-loud red quasars are known to be X-ray sources (Bregman et al., 1985, Elvis et al., 1994), so this is unlikely to be a problem.

Complete flux limited X-ray surveys have found some red quasars or AGN (Stocke et al., 1982, Kruper & Canizares 1989, Puchnarewicz et al., 1996, 1997). In particular the RIXOS survey (Puchnarewicz & Mason 1998) has identified a small sample of red quasars.

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For standard Milky Way composition and dust-to-gas ratio (Bohlin, Savage & Drake 1978, Seaton 1979) the PSPC count rate is reduced by a factor 1/e at $A_V=1.7$ ($N_H = 3 \times 10^{21}$ atoms cm$^{-2}$), for a power-law photon index of 2.0, all at zero redshift.
As part of a more general search for minority populations of X-ray sources we have used the ROSAT (Trümper et al. 1983) archive of pointed PSPC (Pfefferman et al., 1987) data to design an efficient search strategy explicitly targeting red quasars. The ROSAT pointed archive provides us with a tenfold increase in the number of X-ray sources from before ROSAT (to about 70,000), and reaches more than ten times fainter than the ROSAT All Sky Survey (Voges et al. 1996). By carefully selecting a small number of interesting objects we can make an efficient search for a radio-quiet population of red quasars.

In this paper we find a substantial population of radio-quiet red AGN on the quasar/Seyfert luminosity boundary.

2. Sample Selection

Most ROSAT sources at high Galactic latitude are blue, unobscured AGN (e.g. Boyle, Wilkes & Elvis, 1997, Schmidt et al., 1997). We use this fact to efficiently select against such objects and so isolate any red AGN that may be in the ROSAT archive.

As a compendium of the X-ray sources found by the ROSAT PSPC we have used the 'WGACAT' catalog (which is named after its authors, White, Giommi & Angelini 1995). This catalog was generated from ROSAT PSPC pointed observations, using a sliding cell detect algorithm. This method is sensitive to finding point sources, but can also find spurious sources where extended emission is present. WGACAT includes a quality flag that notes such dubious detections based on a visual inspection of the fields. We have only used X-ray sources with high detection quality to exclude the spurious sources. From the WGACAT catalog, we have selected sources by the following criteria:

1. X-ray bright ($f_X > 10^{-13}$ erg cm$^{-2}$s$^{-1}$), to allow follow-up observations with other X-ray telescopes;

2. well-detected with signal-to-noise ratio $>$10 and WGACAT quality flag, DQFLAG $>$5;

3. within r=18 arcmin from the detector center, to provide good positions;

4. at high galactic latitude ($|b| > 20^\circ$), to minimise the fraction of Galactic stars (which are also red);

5. not within 2 arcmin of the target position (at which point the source density reaches the background level), to select only random, serendipitous, sources; and

6. North of decl.$=-18^\circ$ in order to have two band measurements in the Automated Plate-measuring Machine (APM) catalog (McMahon & Irwin, 1992), hence giving an archival optical color.

7. unidentified, with WGACAT class=9999 and no SIMBAD or NED identification $^3$; 

$^3$Although only ‘unidentified’ sources were selected, one (1WGA J1118.0+4505, see Table 1) turned out to be a known Seyfert 1 (Bade et al. 1995).
The first six criteria selected 1624 sources. Since these sources were selected purely on their X-ray properties they form a well-defined sample from which to study the incidence of minority X-ray populations, including any radio-quiet red quasars. Adding the requirement that a source be unidentified left 940 X-ray sources which could be examined for having red optical counterparts.

We then searched the APM catalog of objects detected on the Palomar Sky Survey for optical counterparts to the unidentified X-ray sources. To find counterparts we used a search radius of 26 arcsec, which corresponds to about 95% confidence for X-ray sources within 18 arcmin of the PSPC detector center (Boyle et al., 1995a). 881 sources had APM catalog counterparts brighter than the limiting magnitudes $O < 21.5$ and $E < 20$. (The remaining ‘blank’ fields are the subject of another study, Elvis, Kim & Nicastro 1999, in preparation.) Among these 881 many had only O-band magnitudes (suggesting that they are blue), leaving 575 with O-E colors available.

The combination of the ROSAT X-ray flux and the APM magnitudes allows us to create a rough classification of the X-ray sources in our sample. The two Palomar O (blue) and E (red) magnitudes are close to Johnson B and Cousins R, respectively (Gregg et al. 1996). From the X-ray flux and the two optical magnitudes we can construct a two-color diagram of $\alpha_{ox} - (O - E)$. $\alpha_{ox}$ is defined by the power law index between 2 keV and 2500 Å (Tananbaum et al. 1979; Stocke et al. 1991). This diagram allows us to select red objects and then to reduce the Galactic stellar population among these red objects by selecting the X-ray loud population. Here we make use of the observation that in stellar sources the X-ray flux for a given optical flux is much weaker than in AGNs and clusters (e.g., Maccacaro et al. 1988).

Figure 1a shows Einstein Medium Sensitivity Survey (EMSS) X-ray sources (Stocke et al. 1991) in the $\alpha_{ox} - (O - E)$ plane. This plot clearly illustrates the distinction between Galactic stellar sources and extragalactic sources.

Based on the EMSS source distribution, we divided the ROSAT-APM sources on the same plane (Figure 1b). The O-E APM colors are not as accurate as the EMSS values, which are based on CCD photometry. As a result the spread of observed colors is wider (Figure 1b), and there will be some blue objects in the red zone and vice versa. To create our list of red quasar candidates we first excluded the 128 sources with $\alpha_{ox} > 1.8$, because they are likely to be Galactic stars. Then we excluded another 360 sources with blue colors, $O - E < 2$, because they are most likely just normal blue unobscured AGN. This results in a final sample of 87 X-ray sources defined by the lower-right corner of figure 1b in the $\alpha_{ox} - (O - E)$ plane.

Our sample of 87 optically red X-ray-loud sources is a mere 0.1% of the ~70,000 WGA-CAT sources. The fraction of X-ray sources that may be red quasars though is much larger: ~5% of the initial X-ray selected sample; ~15% of the unidentified sources with APM colors; and ~20% of X-ray bright objects with APM colors which will, primarily, be AGN.

However, other classes of X-ray source than red quasars can inhabit this region of the $\alpha_{ox} - (O - E)$ plane, for example first ranked elliptical galaxies in distant clusters of galaxies. Optical spectroscopy is needed to find red quasars. We have taken spectra for 51 of the 87 red quasar candidates, as described in the next section.

3. Observations
3.1 Optical Spectroscopy

A typical X-ray error circle contains just 1-2 optical objects in the APM catalog. Since we have selected against blue counterparts, we began by observing the brightest red counterpart. If two objects were present we aligned the spectrograph slit to obtain spectra of both at once. If this the first spectra did not find an AGN we then observed the next faintest, if present. Since the density of (blue) AGN at B=21 is only $\sim0.005$ per error circle (e.g. Zitelli et al., 1992) we expect only 1/4 chance AGN coincidences in the 51 spectra, so stopping once an AGN is found will not produce a significant number of false identifications.

We performed optical spectroscopy with MMT on 1997 March 13-15, with the FLWO 60′′ telescope on 1996 November 16-17 and 1997 February 12-13, and with the CTIO 60′′ telescope on 1997 February 3-5. We used long-slit apertures of 2-3′′ × 180′′ and gratings with 300 gpm. The spectral resolutions are 6˚A and 9˚A for the MMT and 60′′ telescopes, respectively. Wavelength coverage is about 3500-8000˚A. We took bias, dome flat and twilight sky frames each night, and the corresponding corrections (bias subtraction, flat fielding, and illumination correction) were applied separately to each night of data. At least 2 standard stars were observed each night for spectrophotometric calibration. The observing conditions were not photometric, except for the CTIO run, so the absolute calibration is subject to a significant uncertainty. However, relative intensities (such as a line intensity ratio and an optical power-law index) are accurate within 20%, as confirmed by multiple observations of the same source. Six sources are of undetermined nature because they are too faint and so gave spectra of too poor a signal-to-noise.

3.2 Classification of Spectra

Of the 45 sources observed at good signal-to-noise, we have identified 7 red quasars (Table 1). The results for these 7 red quasars are presented in this paper. (The full data set will appear elsewhere.) The red quasars are mixed in with 18 stars and a small number of normal blue quasars, narrow emission line galaxies, and elliptical galaxies (Table 1). The elliptical galaxies are likely to be brightest cluster galaxies. We shall report on these separately. For the remaining 9 X-ray sources, the red optical candidate within the error circle turned out to be a star (mostly late type), but it is not likely that these red stars are the counterparts because their $\alpha_{OX}$ values are too large for a star (see above, and Maccacaro et al. 1988). The remaining optical candidates are not red, and hence we stopped making further observations. These 9 sources, and the 3 blue quasars measure the blue contamination of the sample, and should not be considered as part of the list of red X-ray counterparts.

The optical spectra of the 7 red quasars are shown in Figure 2a, b. Broad lines of Hα, Hβ and MgII are clearly seen in the spectra as well as bright narrow lines (e.g., [OIII]λ5007), making the AGN character of the objects unambiguous. In Table 2, we tabulate source position, redshift, optical magnitude and color, X-ray flux and X-ray colors, and $\alpha_{OX}$ as well as offsets between the optical and X-ray positions.

In Figure 1b, each class of identified sources are plotted in the $\alpha_{OX} - (O - E)$ plane. The distribution of these sources can be compared with the EMSS sources in Figure 1a, confirming that most X-ray sources with low $\alpha_{OX}$ are indeed quasars or galaxy clusters. The selection technique finds 7/51 red quasars, i.e. 8% efficiency. A slightly stricter criterion,
\(\alpha_{ox} < 1.6\) (instead of 1.8), would have selected red quasars more efficiently (Table 2, Figure 1b): only one M star (instead of 19 stars) would have been present, with only one red quasar lost, i.e. 6/29, a little over 20%. Of the initial 87, 71% (62) remain when \(\alpha_{OX}=1.6\) is the boundary.

### 3.3 Observed Optical Properties of the Red Quasars

We measured the optical continuum slopes by fitting a power law to the continuum spectra, after excluding the strong emission lines (Table 3). Although all the sources were selected based on a red \(O−E\) color, in some cases the observed optical continuum shape is relatively flat. This is both because line emission contributed to the blue and/or red bands, and because of uncertainties on the O and E magnitudes, particularly when the object is faint (M. Irwin, private communication). The power law index \(F_\nu \sim \nu^{\alpha_{opt}}\) ranges from −0.9 to −2.6. A steep optical continuum, \(\alpha_{opt} < −2\), is found in 5 of the 7 red quasars, while even the remaining 2 ‘intermediate’ red quasars are redder \((-1.5 < \alpha_{opt} < -1)\) than found for UV excess selected quasars \((-0.2\pm0.8,\) Neugebauer et al., 1987). To illustrate the spectral differences between these two groups, we display the spectra separately in Figure 2a (steep) and Figure 2b (intermediate).

In addition to the difference in continuum shape, these two groups also differ in their \(H\beta\) line strengths (see Figure 2a, b). The group with the steep optical continuum have only weak \(H\beta\) lines or no detection, whereas the group with a relatively flat continuum have stronger \(H\beta\) lines. Since the ratio of \(H\alpha\) to \(H\beta\) is sensitive to optical extinction, this suggests more reddening in the ‘steep slope’ group than the ‘intermediate slope’ group (Table 3), in accord with the optical continuum slopes.

To quantify this effect for those quasars with no detected \(H\beta\) line, we estimated its upper limit using a simple method that assumes a box profile with a base equal to 3000 km sec\(^{-1}\) (the mean FWHM of detected \(H\beta\) lines), and a height equal to three times the fluctuation noise on the continuum. This is a conservative measurement because the peak of a Gaussian profile would be more easily detected than the flat top of a box profile, particularly when the line width is considerably larger than the spectral resolution. Monte Carlo simulations using a Gaussian line profile assuming Poisson statistics show that the box profile overestimates the upper limit by up to 50% for the adopted line width, while it reproduces consistent results when the line width is comparable to the spectral resolution. For the two objects whose optical spectra do not cover the \(H\alpha\) line we have instead used the \([OIII]/H\beta\) ratio as a measure of relative \(H\beta\) strength.

| \(\alpha_{ox} \geq 1.6\) (\(O\geq19\)) | Total | Red Quasars | Too Faint | NLXG | Elliptical Galaxies | M Stars | Other Stars | Blue Quasars | Not Red |
|---|---|---|---|---|---|---|---|---|---|
| 1.8 > \(\alpha_{OX} > 1.6\) | 22 | 1 | 0 | 0 | 1 | 17 | 1 | 0 | 2 |
| \(\alpha_{OX} < 1.6\) (\(O<19\)) | 29 | 6 | 6 | 2 | 4 | 1 | 0 | 3 | 7 |
| **Total** | 51 | 7 | 6 | 2 | 5 | 18 | 1 | 3 | 9 |
For all 5 quasars with $\alpha_{\text{opt}} > 2$, the $H\alpha/H\beta$ ratios are greater than 5, while the $\text{[OIII]}/H\beta > 0.8$. The line ratios of the two remaining, quasars are smaller (Table 2), consistent with less reddening in intermediate slope objects.

None of the characteristic galaxian stellar absorption features are seen in our spectra. Most strikingly no 4000Å break is seen in any of the five red quasars for which our spectra cover that region, including all of the steep slope group. Typical values of $D(4000)^5$ are 1–1.2, as expected from the measured optical slopes. These compare with values of 2±0.2 for normal E and S0 galaxies Dressler & Shectman (1987). Hence any starlight continuum contribution to the red quasar continuum must be minor.

### 3.4 X-ray Colors of the Red Quasars

To determine the rough X-ray spectral properties of the 7 red quasars we first double-checked in the PSPC images that the sources were cleanly separated from any confusing sources, and then measured their X-ray hardness (HR=H/M) and softness (SR=S/M) ratios based on the count rates in the standard ROSAT PSPC bands: Soft, S (0.1-0.4 keV), Medium, M (0.4-0.86 keV), and Hard, H (0.87-2 keV). These ratios are then converted to effective X-ray spectral indices $\alpha_{\text{soft}}$ and $\alpha_{\text{hard}}$ (Table 2), to correct for the variable Galactic line-of-sight absorption, and the energy-dependent PSF. [These are not physical slopes, but should be considered analogous to U-B and B-V colors, see Fiore et al. (1998) for a detailed discussion of the estimation and usage of effective X-ray spectral indices.] Due to the low signal-to-noise ratio of X-ray data, individual spectral indices are not reliable. However, the locus of their colors forms a useful indicator of global X-ray properties.

We compare the colors of the red quasars with those of normal radio-quiet quasars in Figure 3. The large filled symbols are the red quasars reported here, while the cloud of small dots are radio-quiet quasars from the sample of Fiore et al. (1998). On average the red quasars have smaller $\alpha_{\text{soft}}$ than $\alpha_{\text{hard}}$, indicating a cut-off spectral shape. [The line pairs around the periphery of the figure show outline spectral shapes for their locations in the $(\alpha_{\text{soft}},\alpha_{\text{hard}})$ plane.] This is consistent with their having the moderate X-ray absorption expected from their optical properties (Fiore et al., 1998a).

### 4. Discussion

These observations show that a population of red AGN can be extracted efficiently from the ROSAT pointed archive. Moreover the red AGN we find are radio-quiet. None of them is a radio source in the VLA NVSS survey ($f_{1.4GHZ} < 2.5$ mJy, Condon et al., 1998) implying $R_L = log[f(\text{opt})/f(5GHZ)] < 2.0$, compared with $2 < R_L < 5$ for radio-loud quasars (Wilkes & Elvis 1987). The agreement of X-ray colors, optical continuum slope and $H\alpha/H\beta$ ratios with the same value of obscuring dust and gas ($A_V \sim$1-2) argues for their being dust reddened objects rather than intrinsically red continua.

Puchnarewicz & Mason (1988) discuss a similar population of 14 candidate red, $\alpha_{\text{opt}} > 2$, AGN derived from the ‘RIXOS’ sample, which extends to several times fainter X-ray fluxes. The RIXOS sample was selected from the ROSAT pointed archive based on X-ray flux

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4 CH g-band4304, MgI 5175, Ca+Fe 5269, NaI 5890, 5896.
5 $D(4000) = F_\nu(4050 - 4250\text{Å})/F_\nu(3750 - 3950\text{Å})$, Dressler & Shectman (1987).
Table 2: Basic Properties of Red Quasars

| name            | RA       | DEC       | offset  | z     | $f_X^c$ | $\alpha_{soft}^d$ | $\alpha_{hard}^d$ | O      | O-E    | $\alpha_{OX}$ |
|-----------------|----------|-----------|---------|-------|---------|-------------------|-------------------|--------|--------|----------------|
| J2255.5+0536    | 22 55 31.0 | 05 36 01 | 11.3    | 0.0647 | 7.74    | 1.459             | 0.750             | 16.38  | 2.44   | 1.636          |
| J1234.3+2614    | 12 34 21.8 | 26 13 28 | 5.0     | 0.3120 | 2.42    | 0.860             | 1.711             | 20.55  | 2.35   | 1.180          |
| J1218.1+2956    | 12 18 07.1 | 29 55 21 | 4.3     | 0.1514 | 1.62    | 0.959             | 1.512             | 19.16  | 2.08   | 1.466          |
| J0909.7+4302    | 09 09 43.6 | 43 02 47 | 7.0     | 0.2748 | 1.65    | 0.859             | 1.417             | 21.38  | 2.28   | 1.114          |
| J1143.6+5521    | 11 43 35.5 | 55 20 21 | 4.0     | 0.1467 | 1.52    | 0.535             | 1.040             | 19.33  | 2.33   | 1.451          |

$(-0.9 > \alpha_{opt} > -2.0)$

| name            | RA       | DEC       | offset  | z     | $f_X^c$ | $\alpha_{soft}^d$ | $\alpha_{hard}^d$ | O      | O-E    | $\alpha_{OX}$ |
|-----------------|----------|-----------|---------|-------|---------|-------------------|-------------------|--------|--------|----------------|
| J1051.4+3358    | 10 51 28.3 | 33 58 04 | 8.0     | 0.1829 | 2.76    | 1.290             | 1.295             | 18.27  | 2.72   | 1.515          |
| J1142.6+4624    | 11 42 41.2 | 46 24 21 | 3.1     | 0.1151 | 15.75   | 0.926             | 1.263             | 16.33  | 2.44   | 1.522          |

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**Note:**

- RA and DEC: optical coordinate in Equinox J2000.
- offset: difference of X-ray and optical positions in arcsec.
- $f_X$ in units of $10^{-13}$ ergs$^{-1}$ cm$^{-2}$.
- $\alpha_{soft}$: X-ray spectral index in 0.1 - 0.8 keV.
- $\alpha_{hard}$: X-ray spectral index in 0.8 - 2.0 keV.

Table 3: Line, Continuum Properties and Luminosities of Red Quasars

| name            | $\alpha_{opt}^a$ | H$\alpha$ | M(O) | M(E) | $L(X)^o_{43}$ |
|-----------------|------------------|----------|------|------|---------------|
|                 |                  | FWHM     | f$^e$| L$^d$|               |
|-----------------|------------------|----------|------|------|---------------|
| $(\alpha_{opt} < -2.0)$ |
| J2255.5+0536    | -2.39            | 5962     | 29.8 | 0.54 | -21.6         | -24.1 | 1.02          |
| J1234.3+2614    | -2.64            | 7184$^e$ | 5.1$^e$ | 2.70$^e$ | -21.1         | -23.5 | 8.19          |
| J1218.1+2956    | -2.36            | 5011     | 5.2  | 0.56 | -20.8         | -22.9 | 1.21          |
| J0909.7+4302    | -2.43            | 2178     | 2.3  | 0.91 | -20.0         | -22.3 | 4.29          |
| J1143.6+5521    | -2.11            | 3223     | 5.1  | 0.51 | -20.5         | -22.9 | 1.07          |
| $(-0.9 > \alpha_{opt} > -2.0)$ |
| J1051.4+3358    | -0.93            | 1797$^f$ | 7.1$^f$ | 7.10$^f$ | -22.1         | -24.8 | 3.07          |
| J1142.6+4624    | -1.41            | 3104     | 81.3 | 4.90 | -23.0         | -25.4 | 6.75          |

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**Note:**

- $\alpha_{opt}$: optical spectral index, $f_{nu} \propto \nu^{-\alpha_{opt}}$.
- $L(X)_{43}$ in units of $10^{43}$ erg s$^{-1}$.
- $f_{line}$ in units of $10^{-15}$ erg cm$^{-2}$ s$^{-1}$.
- $L_{line}$ in units of $10^{43}$ erg s$^{-1}$.
- MgII.
- H$\beta$. 

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**Add D4000?**
alone. (There is one object in common between the two samples.) Two of the red RIXOS AGN may be intrinsically red, and three have clear reddening. So there is currently a total of 8 reddened AGN available from ROSAT.

The red AGN, both from this sample and from RIXOS, are borderline quasar/Seyfert objects. The observed optical luminosities of the red AGN are modest, lying at the high end of the traditional Seyfert luminosity range ($M_B > -23$ mag, Veron-Cetty & Veron 1984, Schmidt & Green 1983): from $M_O = -20$ to $M_O = -22$ mag. The dereddened, intrinsic luminosity of the sources is likely to be significantly higher, depending on the amount of absorption (the lower limit on the extinction is 2-3 mag in O). This places them at $-25 < M_O < -22$, within the quasar regime. Similarly, the observed X-ray luminosity ranges from $1.3 \times 10^{43}$ to $1.2 \times 10^{44}$ erg sec$^{-1}$, while the intrinsic luminosities are likely to be higher by about a factor of 2, depending on the intrinsic spectrum and the amount of absorption present.

The precise allocation of these AGN as quasars or Seyferts is not fundamentally very interesting, since this is just a conveniently chosen value on a continuous luminosity scale. For simplicity we will refer to them as ‘red quasars’ for the rest of this paper. It is, however, interesting to understand why much more, or much less, luminous AGN were not found in the two red quasar searches. Is this a selection effect, or is there a physical preference for red objects to cluster in a limited range of luminosity? We shall return to this question later (§4.3).

The existence of a red quasar population immediately raises important questions: What makes them red, compared to usual blue quasars? How common are they, particularly once allowance is made for their reduced flux due to probable obscuration? If they are absorbed, then by how much? Where is the absorbing dusty material? Might a larger, more obscured, AGN population exist?

4.1 How Common are Red Quasars?

We can address the relative numbers of red quasars in a rough way. The population, although a minority, is quite common. We found 7 red quasars out of 45 candidates for which our spectroscopy was adequate to produce a classification. Assuming the 45 were a random subsample of the original sample of 87, then that sample would produce 14 red quasars. This is 2.4% of 575 sources with optical colors available. At our flux limit Stocke et al. (1991) find that 51% of all X-ray sources are AGN. So a minimum of 13.5/288 = 4.7% of AGN in our ‘unidentified sample’ are radio-quiet red quasars (with O<20) at this soft X-ray flux level. The Boyle & di Matteo (1995) upper limit of 9% of CRSS X-ray sources being red quasars is consistent with the minority population of moderately obscured ($A_V=2$) quasars we have found here.

Additional red quasars could be hidden in our sample. Our sample of 45 classified spectra is not a random subsample of the candidate list. Figure 1b shows that we preferentially selected objects with $\alpha_{OX} > 1.3$, i.e. the brighter objects (with B<21.5). If the 6 objects for which we attempted to get spectra turn out to be red quasars then the fraction of red quasars among the PSPC AGN could be almost double our first estimate. There are a further 36 red candidates for which no spectroscopy was attempted. So the true occurrence

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6We have used $H_0 = 50$ km sec$^{-1}$ Mpc$^{-1}$ and $q_0 = 0$. 
rate of red quasars is uncertain by a factor 7.

To find the fraction of red quasars among all the AGN in our X-ray flux limited sample we must allow for the 165–300 blue AGN in the ‘identified’ sample, so 1% – 7% of the whole soft X-ray AGN population is red.

If the red AGN are obscured then the intrinsic rate of occurrence of red quasars has to be calculated relative to their unreddened parent population. Obscuration by $A_V = 2$ reduces their unobscured X-ray fluxes by a factor $\sim 2$. Since higher flux AGN are rarer (the X-ray selected AGN $\log N - \log S$ relation has a slope of $-3/2$ in this flux range, Hasinger 1992, Della Cecca et al., 1992), the red population forms a larger fraction of this population, $\sim 3\% - 20\%$.

Using the fraction of the sources at the intrinsic flux of the red quasars allows us to compare our result with samples unaffected by obscuration, and with model predictions. Comparisons with the observed frequency of radio-loud red quasars with broad emission lines found by Smith and Spinrad (1980, 178 MHz 3CR) and Stickel et al. (1996, 5GHz “1Jy” sample), and with the Comastri et al. (1995) predictions are straightforward.

Red quasars are found in 15% of the 3CR source sample and 6%-20% of the 1 Jy (Carilli et al., 1998) sample. These are comparable with the 3% - 20% of the ‘intrinsic flux’ X-ray population that we find, suggesting that the radio-loud and radio-quiet quasar populations have similarly sized populations of moderately obscured quasars. The obscuration in the 3CR red quasars is also about $A_V=2$ (Elvis et al., 1994, Economou et al., 1995, Rawlings et al., 1995). For four objects in the 1Jy sample Carilli et al. (1998) estimate lower limits on $A_V$ from 2 to 5, based on extrapolating the radio-infrared index to the optical. However, since such steeply rising slopes are not known among unobscured quasars, these limits are likely to be too large, and values comparable with the 3CR estimates are probably acceptable.

For AGN with $N_H < 10^{22}\text{cm}^{-2}$ the Comastri et al.(1995) model predicts that 26% will have $10^{21} < N_H < 10^{22}\text{cm}^{-2}$ ($A_V \sim 2$), somewhat larger but comparable with the numbers found here. Comastri et al. predict far larger numbers of more obscured objects.

4.2 More Obscured Objects

More obscured objects may exist. Puchnarewicz & Mason (1998) find several objects with steeper optical continua, and figure 1b shows several redder candidates and many more x-ray loud candidates, with no optical spectra to date. Webster et al. (1995) suggested that $A_V=5$ may be typical of their red objects, giving their putative ROSAT counterparts in our sample $V=23-25$ which is below the Palomar Sky Survey limit. $A_V=5$ corresponds to a column of $9 \times 10^{21}\text{atoms cm}^{-2}$, which would reduce ROSAT PSPC count rates to 15% of their unobscured values. These objects would then be hidden as a 6% minority among the more common lower luminosity unabsorbed quasars if they had the same unobscured space density as normal blue quasars. Some 9% of our initial X-ray selected sample are ‘blank field’ objects, i.e. have no counterpart on the Palomar Sky Surveys. A fraction of these could be more heavily obscured red quasars. Boyle & di Matteo (1995) find that the CRSS sample could be missing no more than 9% (at the observed flux) in red quasars. Subtracting the 1% of moderately obscured quasars that we have identified this still leaves 8% that could be highly obscured. Hence the CRSS result is, perhaps surprisingly, consistent with a sizeable, heavily obscured, population. The Comastri et al. (1995) model predicts a comparable population of AGN with $N_H \sim 10^{22}\text{cm}^{-2}$, 1.1 times larger than the unobscured population.
In our sample the occurrence of red quasars appears to be four times higher for O > 19 mag (4/12) than for O < 19 mag 3/32 (Table 2), although the number of sources is small. Such a trend is expected if the quasars are heavily absorbed. An increase in $N_H$ from $3 \times 10^{21}$ cm$^{-2}$ to $1 \times 10^{22}$ cm$^{-2}$ cuts the ROSAT flux by a factor 2.4, but reddens the V-band by 3.8 magnitudes (a factor 33). So the optically fainter sources might well be redder. However the RIXOS red quasars (Puchnarewicz & Mason 1998) show no correlation of optical slope with $m_V$ - the three steepest slopes are all in the brighter half of the sample of 14. Gunn & Shanks (1998) have pointed out that, while redshifting the ultraviolet into the optical increases the effects of reddening, the corresponding shift of hard X-rays into the soft ROSAT band decreases the effectiveness of reddening.

To estimate an accurate fraction of this potential hidden population needs a larger sample, including more absorbed, fainter objects. At even larger column densities ($10^{23}$-$10^{24}$ cm$^{-2}$) the Comastri et al.(1995) model predicts nearly four times the unobscured population. More heavily obscured quasars could be found in hard X-ray surveys, from ASCA (Ueda et al., 1998), and the Beppo-SAX ‘HELLAS’ survey (Fiore et al., 1999).

4.3 Limited Luminosity Range

It is striking that while ROSAT surveys that are defined simply by an X-ray flux limit find AGN spanning over 3 decades in X-ray luminosity (e.g. ‘CRSS’ Boyle, Wilkes & Elvis 1997, RIXOS, Puchnarewicz et al., 1996), both RIXOS and this survey find red quasars in only one decade of luminosity, and that this decade is the lowest in which RIXOS and CRSS AGN are found. A 2-tail Kolmogorov-Smirnov test shows that the chance that red and non-red AGN from RIXOS come from the same luminosity distribution is only ~2%. This suggests that predominantly lower luminosity AGN are obscured. [Note that the observed amount of obscuration only decreases the observed X-ray luminosity by a factor of ~2, and so does not itself cause the low observed luminosities.]

Similar suggestions have been made before: Lawrence & Elvis (1982) found that only AGN below $L_X \sim 10^{44}$ erg s$^{-1}$ (2-10 keV) showed obscuration. Occasional examples of highly obscured ‘type 2’ (i.e. narrow line) quasars have been reported (Stocke et al., 1982, Almaini et al., 1995, Shanks et al., 1995), and careful searches have found broad H$\alpha$ in most cases (Halpern, Eracleous & Forster 1998), making them similar to the red quasars found here. Searches among the fainter objects in our sample and searches at higher energies (e.g. the BeppoSAX ‘HELLAS’ survey, Fiore et al., 1999) will be more effective at finding a high luminosity red quasar population.

The Comastri et al. X-ray background models assume luminosity functions for the obscured objects that are identical to those of the unobscured objects, except for normalization and so predicts high luminosity red quasars. If instead obscured AGN occur preferentially at low luminosity this will substantially affect the model predictions. We would, for example, expect the obscured population to be more numerous and at lower redshift.

If there is a real deficit of high luminosity red quasars, then one possibility to explain this lack might have been that as an AGN became more luminous the continuum ionized the obscuring medium, rendering it transparent to X-rays. However ionized absorbers are also more common at lower luminosities (Laor et al., 1994). So most likely high luminosity AGN have fewer lines of sight with intervening material regardless of ionization state. Interestingly this is in the same sense as the Baldwin effect: that higher luminosity quasars have
weaker CIII]1909 emission lines.) Any physical model of a quasar would need to explain this difference.

### 4.4 Physical Properties

We can say only a little about the physical properties of the red quasars from this data. The consistency of the optical reddening indicators with the X-ray colors suggests that the same obscuring material covers both emitting regions, and that it lies outside the broad emission line region.

Smith and Spinrad (1980) suggested that the redness of the red 3CR quasars is intrinsic to the continuum emission process, based on the lack of an absorption feature at $\lambda = 2200\AA$, which is a typical characteristic of Milky Way dust (e.g., Bless and Savage 1972). The detection of 21 cm HI absorption toward a large fraction of the 1Jy (Stickel et al., 1996) red quasars (Carilli et al., 1998) argues for dust reddening in those objects. Since our sample of radio-quiet quasars is relatively nearby (with redshifts up to 0.3), we can not check for this feature directly. However, this explanation is in contrast to the observed Balmer decrement, and the X-ray colors. It is possible that the reddened 3CR sources contain dusty, ionized absorbers, as seen in 3C212 (Mathur 1994; Elvis et al. 1994) and IRAS17020+4544 (Komossa & Bade 1998), where the dust composition may differ depending on, for example, the quasar continuum shape. Ultraviolet observations are needed to investigate the $\lambda = 2200\AA$ feature, but are probably infeasible at present.

### 4.5 Other Red AGN

Some previous studies have considered red AGN-like objects in X-ray surveys:

The RIXOS survey (Puchnarewicz & Mason, 1998) found that 9% (14/160) of their AGN were red. However, only 3 of the RIXOS sources have Balmer decrements that require reddening, so the true occurrence rate of reddened objects may be similar to that which we have found. The fainter flux limit of the RIXOS survey may render more absorbed objects visible. Certainly, the steeper optical slopes ($2.5 < \alpha_{\text{opt}} < 4.0$) of half the RIXOS sample suggest greater reddening.

Kruper and Canizares (1989) studied red AGNs in Einstein X-ray selected samples and indirectly concluded that these are red due to the presence of host galaxies. Benn et al. (1998) arrive at a similar conclusion for low frequency selected radio-loud quasars. However no galaxian starlight features are seen in our spectra and the host galaxy cannot explain the observed Balmer decrements in our sample. The Kruper & Canizares objects are not as red as our samples, having B-I= 1.5 to 2.5 mag. If we take R-I to be 0.5 - 1.0 mag (this is the R-I range of the samples in their table 2), B-R would be less than 2.0, our defining threshold. In fact none of their objects with measured R magnitudes exceed B-R = 2.0.

The Narrow Line X-ray Galaxies (NLXGs) found plentifully in deep ROSAT surveys (e.g. Boyle et al., 1995a), are also normally assumed to be obscured AGNs (e.g. Hasinger et al. 1998, Schachter et al., 1998). X-ray absorbed NLXGs could contribute significantly to the cosmic X-ray background if they are more common at fainter X-ray flux levels, as suggested by McHardy et al. (1998, see also Hasinger et al. 1998 for a cautionary note). Although they have similar X-ray luminosities to the NLXGs, the X-ray selected red quasars are not simply the same population, however. The red quasars have the normal broad optical emission lines of quasars, while NLXGs have either none, or only extremely weak ones.
(Boyle et al., 1995b, c.f. our Figure 2a,b). Moreover, NLXGs usually exhibit blue optical continua (for example, O-E < 2 for 5 out of 6 NLXGs in CRSS, Boyle et al. 1997), while red quasars have red optical continua (O-E > 2). Further X-ray and optical study of these objects may let us understand whether they are two separate populations or are related by e.g. special viewing geometry or scattering of a blue continuum.

The Palomar survey of the nuclei of bright galaxies (Ho, Filippenko & Sargent, 1997) is based on a sample of galaxies selected for their non-nuclear properties and so is less biased against finding red AGN than most other optical search methods, The Palomar AGN are low luminosity AGN, allowing us to see if the high incidence of red AGN at lower luminosities continues to increase at even lower values. The Palomar survey finds that 18% (8/44) of Seyfert nuclei have AV > 2, based on their narrow line Balmer decrements (Ho, Filippenko & Sargent 1997). However almost all of these are LINERs or type 2 Seyferts, which may have large reddening toward the broad line region. Only one Seyfert (NGC7479) shows any evidence for a broad line component. Broad emission lines are extremely hard to detect at these flux levels, but the suggestion is that the middling luminosities, toward the Seyfert/quasar borderline are particularly prone to moderate obscuration.

5. Conclusions

Radio-quiet red quasars can be found in substantial numbers. They comprise at least 1%, and potentially 7%, of the soft X-ray population in a flux limited survey. Correcting the X-ray fluxes to their intrinsic values puts them among brighter AGN where they form 3% of the population. Allowing for ‘blank field’ sources as much as 20% of ROSAT selected quasars may be red, at a given unobscured flux. The size of this population is consistent with previous upper limits, with the Comastri et al. (1995) model for the X-ray background, and with the size of the radio-loud 3CR and ‘1Jy’ red quasar populations. Red quasars seem to be preferentially lower luminosity objects on the Seyfert/quasar borderline, but not at higher or lower luminosities. Such a bias against obscured high luminosity objects would affect X-ray background estimates for this population, and would need explaining in a physical model of quasars.

We stress that the quasars we find have broad optical lines. They are not Narrow Line X-ray Galaxies which, by contrast, have predominantly narrow optical permitted lines and blue continua.

The optical slopes, Hα/Hβ ratios, and X-ray colors are all consistent with reddening by AV ~2, assuming standard Milky Way dust properties. So the same obscuring material probably covers each of the emitting regions.

A significant population of more highly obscured (AV=5) quasars could well exist and be consistent with the results here, with earlier ROSAT limits, and would be as predicted by the Comastri et al. (1995) model. Hard X-ray surveys will soon settle the question of the size of any such population.

Using a minor refinement of the technique presented here, red quasars can be found with high (20%) efficiency in the ROSAT data.

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Figure Captions

Figure 1. (a) Optically identified EMSS sources in the $\alpha_{ox} - (O-E)$ plane. Different sources are marked by different symbols. Our source selection criteria ($O - E > 2$ and $\alpha_{ox} < 1.8$) are seen as a lower-right box. (b) Same as (a) but for our ROSAT samples. The $\alpha_{OX}$ line shows how a slightly stricter criterion yields a larger fraction of red quasars.

Figure 2. (a) Observed spectra of the 5 radio-quiet red quasars ($O-E > 2$ mag and $\alpha_{opt} > 2.0$). Broad lines such as $H\alpha$, $H\beta$ and $MgII$ are clearly seen in the spectra as well as bright narrow lines (e.g., [OIII$\lambda5007$]). Those strong lines are marked in the figures. Steep continuum slopes and very weak $H\beta$ line strengths indicate a significant amount of dust extinction ($A_V > 2$ mag), in contrast to (b) two quasar spectra with $\alpha_{opt} < 2.0$ and relatively strong $H\beta$ lines.

Figure 3. Effective soft and hard ROSAT PSPC X-ray spectral indices (see text) of the red quasars (large filled symbols), compared with normal radio-quiet quasars (small dots, Fiore et al., 1998). Steep optical spectrum $\alpha < -2$) red quasars are shown as circles, intermediate optical spectrum $-1.5 < \alpha < -1$) red quasars are shown as triangles. The line pairs around the periphery of the figure show outline spectral shapes for their locations in the ($\alpha_{hard}, \alpha_{hard}$) plane.
