A Chandra mini-survey of X-ray weak quasars

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ABSTRACT

We present Chandra observations of 18 spectroscopically selected quasars, already known to be X-ray weak from previous ROSAT observations. All the sources but one are detected by Chandra, and spectral analysis suggests that most of them are intrinsically underluminous in the X-rays (by a factor from 3 to > 100). These objects could represent a large population of quasars with a Spectral Energy Distribution different from that of standard blue quasars. We discuss the possibility that a significant fraction of the obscured AGN needed in Synthesis models of the X-ray background could be instead optically broad-line, X-ray weak quasars.

Subject headings: Galaxies: AGN — X-rays: diffuse background

1. Introduction

The blue optical spectrum has normally been used to distinguish quasars from stars and normal galaxies in optical surveys (BQS, Schmidt & Green 1986; LBQS, Foltz et al. 1990; 2dF, Boyle et al. 2000). As a consequence, our knowledge of quasars is by definition limited to “blue” quasars. However, many different quasar SED could exist, undiscovered because of the limits of the available instruments and selection criteria (Elvis 1992). The X-ray properties of optically selected quasars show a similar homogeneity: the 1-10 keV spectrum is well represented by a power law with photon index $\Gamma \sim 1.8 - 2$ (Laor et al. 1997, Reeves & Turner 2000); the average optical to X-ray slope for optically selected samples is $\alpha_{OX} = 1.55$

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Only a minority of objects (<10%) are significantly weaker ($\alpha_{OX} > 1.8$) than the average in the 0.5-2 keV X-ray band (Yuan et al. 1998).

When quasars are searched with selection criteria other than the U-B color, different properties emerge. Webster et al. (1995) found a large population of red broad-line quasars in radio surveys. Kim & Elvis (1998) discovered red quasars in soft X-ray selected samples. Most strikingly, the 2MASS survey (Skrutskie et al. 1997) found a large number of red quasars, whose density is of the same order of that of local color-selected quasars (Cutri et al. 2001). A Chandra survey of these objects revealed X-ray properties completely different from “normal” quasars: the X-ray emission is much weaker and the spectra are flatter, suggesting that these objects suffer significant absorption by circumnuclear gas (Wilkes et al. 2002). The existence of these populations is important. Synthesis models for the X-ray (Comastri et al. 1995, Gilli, Salvati & Hasinger 2001) and FIR (Risaliti, Elvis & Gilli 2002) backgrounds depend sensitively on knowing the true AGN population. Similarly, the total accretion luminosity of the Universe (Fabian & Iwasawa 1999) and the average efficiency of black hole accretion (and hence spin, Elvis, Risaliti & Zamorani 2002) depend primarily on these “hidden” populations.

Another indication of unexpected X-ray properties of non-color selected quasars comes from the work of Risaliti et al. 2001 (hereafter R01), where a sample of spectroscopically selected quasars of the Hamburg survey (Hagen et al. 1995) has been cross-correlated with the WGA Catalogue of ROSAT pointed observations (White, Giommi & Angelini 1995). More than half of the resulting sample is underluminous in the X-rays, by a factor from $\sim 5$ to $>100$. Interestingly, most of these objects are somewhat redder than “normal” quasars ($\Delta(B-R) \sim 1$ vs. $\Delta(B-R) \sim 0.5$, R01), and would have been probably missed in standard color-based surveys, since we expect their U-B color also to be redder than the average of standard blue quasars. Almost all the objects in this sample were not detected by ROSAT, therefore the claim on their X-ray weakness is based on upper limits. As a consequence, nothing is known about their X-ray spectral properties.

The subarcsecond beam size of the Chandra mirrors (van Speybroeck et al. 1997) and the large collecting area endows Chandra with far greater sensitivity than ROSAT. Hence, a Chandra survey can explore the X-ray sample of quasars far better than ROSAT. Here we present the results of Chandra observations of 18 objects selected from the X-ray weak sample of R01.

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\(^3\alpha_{OX}\) is defined as the spectral index of a power law connecting the points at 2500 Å and at 2 keV (rest frame) of the quasar SED in the ($\nu, f_\nu$) plane.
2. Sample selection and observations

The parent sample was obtained by R01 from the cross-correlation of the Hamburg Quasar Survey (hereafter HS, Hagen et al. 1995) with the WGA Catalogue. The HS sample consists of 397 quasars, with redshift between 0 and 3, and limiting magnitude $B \sim 19 - 19.5$. The selection criteria are either the standard U-B colour or the presence of broad emission lines (or both) in grism optical spectra. In this way it is possible to discover objects with intrinsically red continua, or with moderate extinction.

The R01 sample contains 85 sources, of which only 31 were detected by ROSAT. In Fig. 1 we show the distribution of X-ray to optical ratios for this sample, compared with the one of PG quasars. We adopted an index, defined in R01 as $I_{OX} = \frac{20 - B}{2.5} - \log \phi$, where $\phi$ is the ROSAT 0.5-2.4 keV count rate. The reason for using this new index, instead of $\alpha_{OX}$, is that it uses the observed optical data since, with these redder quasars, an extrapolation to 2500 Å may be problematic. For quasars with a standard SED, $I_{OX} \sim 2.6\alpha_{OX} - 1.3$.

The detected sources in R01 have a rather normal X-ray to optical ratio, while the 54 non-detections are X-ray weaker than most PG quasars. The dashed vertical line in Fig. 1 ($I_{OX} = 3.2$) represents the value at which the underluminosity in the X-ray is a factor of 5 with respect to the average of PG quasars. In the following we refer to $I_{OX} > 3.2$ as “X-ray weak” sources.

We randomly selected 17 sources from the X-ray weak half of the sample. As a control sample we included three HS quasars not detected by ROSAT but with upper limits on $I_{OX}$ lower than 3.2.

As shown by R01, there is a strong correlation between the optical O-E color, obtained from the POSS plates, and the X-ray to optical ratio. As a consequence, our 17 X-ray weak sources, being a representative sub-sample of the X-ray weak quasars of R01, are automatically also a representative sub-sample of the red quasars present in the Hamburg Survey, i.e. those objects that would have not been selected by optical color-based surveys.

18 out of the 20 sources of the sample have been observed with the ACIS-S detector on Chandra (Weisskopf et al. 2001) in the year 2002. Out of these 18 objects, 16 are from the X-ray weak group, and the remaining 2 are from the small group of 3 control sources. The observing times vary from 4 to 10 ksec, given the B magnitude of the sources. The observing times were chosen in order to have the same lower limit on $\alpha_{OX}$ for all the sources, in case of non-detection with Chandra. All the sources but one have been detected. The net source counts range from a few tens counts to $\sim 1000$ for a few bright objects (Tab. 1).
3. Analysis and Results

The data were analyzed using the latest ACIS calibrations provided by the Chandra X-ray Center. A correction was applied to the response matrices to account for the low energy quantum efficiency degradation of the ACIS detector. We analyzed the ACIS spectra using a simple model, consisting of an absorbed power law. Both the photon index, $\Gamma$ and the absorbing column density $N_H$ were left free. (Table 1) In Fig. 2 we show the results for the 16 objects of the X-ray weak sample, compared with the spectra estimated from the B magnitudes, assuming the normal UV-selected value of $\alpha_{OX} = 1.55$ (shaded band in each panel of Fig. 2). We calculated $\alpha_{OX}$ deriving the monochromatic flux at 2500 Å from the B magnitude, assuming a spectral shape $f_\nu \propto \nu^{-0.5}$. This is a conservative assumption because the optical colors of these objects are on average redder than in normal quasars. Since for all but three sources the B magnitude central wavelength ($\lambda_B = 4400$ Å) is greater than the redshifted 2500 Å wavelength, using flatter optical spectra would imply higher extrapolations of $f_\nu$ at 2500 Å, and so even higher values of $\alpha_{OX}$. The rest-frame 2 keV flux was directly measured from the spectrum. The results can be summarized as follows:

- 12 out of the 16 X-ray weak sources are confirmed to be extremely faint in the X-rays, with $\alpha_{OX}$ ranging from 1.7 to 2.3. Another object, HS 1417+4522, is only marginally weaker than the average at 2 keV ($\alpha_{OX} = 1.58$), but is significantly weaker than normal AGNs at higher energies (Fig. 2). The spectra are on average slightly flatter than the canonical $\Gamma = 1.8$ (Risaliti 2002): we computed a stacked spectrum of these 13 sources and we obtained an average photon index $\Gamma = 1.5$.
- 3 out of 16 objects have a “normal” $\alpha_{OX}$, significantly higher than the estimate from the ROSAT upper limit. This implies strong variability (of at least a factor $\sim 10$ in the 0.5-2 keV band). Interestingly, these three objects are the only ones in our sample at redshift lower than unity. We will further discuss these sources in a forthcoming paper.
- The two “control sources” both show a “normal” X-ray spectrum. As a consequence, there is no indication that a significant fraction of the sources in the left part of the histogram in Fig. 1 are X-ray weak. Our best estimate of the fraction of X-ray weak quasars in the Hamburg quasars remains the one inferred from the ROSAT observations, i.e. $\sim 50\%$.

4. Discussion

Since 13 out of 16 objects are confirmed to be X-ray weak by Chandra observations, the fraction of X-ray weak sources in the parent sample of R01 is as high as 13/16 of 50%.

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4URL: http://asc.harvard.edu/ciao/threads/apply_acisabs/index.html
i.e. $\sim 40\%$. Since the space density of these sources is of the same order of that found in color-selected surveys with similar limiting magnitudes, these objects represent a significant part of the AGN population. From the X-ray point of view, they appear to be completely different from standard blue quasars both in $\alpha_{\text{OX}}$ and $\Gamma$. In principle, two interpretations are possible for the above results: the sources can be either (1) heavily absorbed or (2) intrinsically X-ray weak.

(1) If absorption plays a crucial role, the observed radiation could be due to warm scattering and/or cold reflection\(^5\) while the intrinsic emission would be absorbed by a column density $N_H > 10^{24}$ cm\(^{-2}\). These objects are somewhat redder than normal “blue quasars” and are all broad line quasars. We would then have an unlikely column density distribution, with all the optically selected blue quasars having $N_H < 10^{21}$ cm\(^{-2}\), all the redder quasars having $N_H > 10^{24}$ cm\(^{-2}\), and nothing in between. This is an argument favoring the alternative hypothesis of intrinsic X-ray weakness.

(2) If the quasars are intrinsically X-ray weak, the accretion disk/corona system could be in a different state than in normal quasars. For example, a weaker corona would naturally produce a weaker X-ray emission. A widely accepted model is that an X-ray emitting corona is generated by the Magneto-Rotational Instability (MRI, Balbus & Hawley 1991). This MRI generates the viscosity in the accretion disk, so if MRI is ineffective little energy should be liberated and the UV continuum and the emission lines should be weak. Yet most most of our objects have been selected through the CIV 1549 Å line, and therefore it is unlikely that they have weak ionizing continua. This paradox clearly needs investigating theoretically. Perhaps MRI does not produce disk viscosity or the bulk of the X-rays in normal quasars have another origin.

Our results show that the current view of the X-ray properties of quasars could be strongly biased by the optical selection towards X-ray loud and steep-spectra objects. This is supported by the fact that the other known red quasars have properties similar to our objects (see for example Wilkes et al. 2001 for Chandra observations of 2MASS quasars).

As can be seen from Table 1, the X-ray luminosities of our sources are in the range $10^{44} - 10^{45}$ erg s\(^{-1}\), only slightly higher than the typical luminosities where the bulk of the X-ray background is made, according to synthesis models (Gilli et al. 2001). Also, the average spectral properties ($\Gamma_{AV} = 1.5$) are close to those needed by these models. It could well be that a fraction of the sources predicted to have $N_H \sim 10^{22} - 10^{23}$ cm\(^{-2}\), used by current synthesis models are instead intrinsically weak, flat spectrum sources, with normal broad

\(^{5}\)Note that diffuse emission from the host galaxies is expected to give little contribution, the observed luminosity being higher than $10^{44}$ erg s\(^{-1}\).
quasar emission lines. If this is the case, the optical/infrared counterparts of these objects would be completely different from those of the standard type 2 AGNs: the optical emission would not be obscured, but could be redder than standard blue quasars, and therefore less readily distinguished from stellar emission. Another important difference with respect to the standard view is that the direct optical/UV emission would not be reprocessed at mid/far IR wavelengths. This would significantly lower the expected contribution of AGNs to the far IR background (Risaliti, et al. 2002) and allowing a larger population of such quasars to be present.

A key test for this hypothesis will be the comparison between the X-ray and optical properties of the sources with X-ray flux $\sim 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ in the Chandra Deep Surveys. These objects have luminosities of the order of $10^{43} - 10^{44}$ erg s$^{-1}$, where the bulk of the XRB is made, and their observations have enough S/N to distinguish between intrinsically weak and absorbed spectra. This will make clear whether the X-ray sources described in this work are also common at lower luminosities.

Another important step to improve the understanding of this class of sources, will be the study of their optical and near-IR spectra: since they are completely different from normal blue quasars in the X-rays, they could also have quite different optical and near-IR SEDs. To explore this issue, we are undertaking optical and near-IR observations of several of the sources in our sample at 4-meter class telescopes.

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Table 1. Data Analysis Results

| Source      | z   | Exp. time\(^{a}\) | Counts | \(\alpha_{\text{OX}}\)^\(^{b}\) | \(\Gamma\)^\(^{c}\) | \(N_{H}\)^\(^{d}\) | L(2-10 keV)^\(^{e}\) |
|-------------|-----|--------------------|--------|-------------------------------|----------------|----------------|----------------|
| HS 0017+2116| 2.02| 10130              | 62     | 1.77                          | 1.79\(^{+0.32}_{-0.36}\) | < 0.81        | 43             |
| HS 0810+5157| 0.38| 6940               | 988    | 1.40                          | 1.56\(^{+0.15}_{-0.07}\) | < 0.14        | 2.7            |
| HS 0830+1833| 2.27| 6480               | 63     | 1.83                          | 1.91\(^{+0.33}_{-0.33}\) | < 0.65        | 4.9            |
| HS 0848+1119| 2.62| 6120               | 47     | 1.76                          | 1.39\(^{+0.53}_{-0.38}\) | < 3.20        | 10.7           |
| HS 0854+0915| 1.05| 3760               | 37     | 2.07                          | 0.67\(^{+0.60}_{-0.53}\) | —             | 1.5            |
| HS 1036+4008| 1.96| 6060               | 51     | 2.12                          | 1.04\(^{+0.66}_{-0.56}\) | —             | 2.5            |
| HS 1111+4033| 2.18| 9760               | 168    | 1.78                          | 2.07\(^{+0.28}_{-0.25}\) | < 0.43        | 11.3           |
| HS 1202+3538| 2.28| 6760               | 52     | 1.79                          | 2.28\(^{+1.18}_{-0.50}\) | < 2.32        | 3.2            |
| HS 1229+4807| 1.37| 6750               | 100    | 1.58                          | 2.17\(^{+0.38}_{-0.31}\) | < 0.15        | 2.9            |
| HS 1237+4756| 1.55| 4750               | 393    | 1.38                          | 1.55\(^{+0.22}_{-0.09}\) | < 0.34        | 12.1           |
| HS 1415+2701| 2.50| 8720               | <15    | >2.3                         | —              | —             | <3             |
| HS 1417+4722| 2.21| 7760               | 132    | 1.58                          | 2.19\(^{+0.46}_{-0.28}\) | < 1.55        | 12.0           |
| HS 1422+4224| 2.21| 5960               | 157    | 1.71                          | 2.45\(^{+0.33}_{-0.44}\) | < 1.10        | 9.4            |
| HS 1824+6507| 0.30| 6950               | 733    | 1.47                          | 1.80\(^{+0.14}_{-0.12}\) | < 0.11        | 1.5            |
| HS 1939+7000| 0.12| 4970               | 1103   | 1.54                          | 0.95\(^{+0.16}_{-0.07}\) | < 0.02        | 0.74           |
| HS 2135+1326| 2.29| 5990               | 53     | 1.88                          | 1.98\(^{+0.83}_{-0.63}\) | < 2.25        | 5.8            |
| HS 2146+0428| 1.32| 7610               | 170    | 1.73                          | 1.88\(^{+0.39}_{-0.30}\) | < 0.55        | 4.1            |
| HS 2251+2941| 1.57| 7110               | 35     | 1.97                          | 1.50\(^{+0.56}_{-0.52}\) | < 2.57        | 1.5            |

\(^{a}\)Exposure time in seconds.

\(^{b}\)\(\alpha_{\text{OX}}\) obtained using the best fit model.

\(^{c}\)Photon index.

\(^{d}\)Column density in units of \(10^{21} \text{ cm}^{-2}\).

\(^{e}\)2-10 keV luminosity in units of \(10^{44} \text{ erg s}^{-1}\).
Fig. 1.— Optical to X-ray ratio as inferred from ROSAT observations for the color-selected PG quasars (shaded histogram) and the sample of R01. $I_{OX}$ is a logarithmic measure of the ratio between optical (B band) and soft X-ray flux.
Fig. 2.— Chandra spectra of the sample of X-ray weak quasars. The shaded region represent the X-ray spectrum expected assuming $\alpha_{OX} = 1.55$ and $\Gamma = 1.8$. ROSAT upper limits are shown for the three sources having fluxes significantly higher than in ROSAT observations.
Fig. 3.— $\alpha_{\text{OX}}$ versus luminosity compared with (a) the average values found by Yuan et al. (1998) for a sample of $\sim 1000$ optically selected quasars (shaded lines), (b) the average $\alpha_{\text{OX}}$ of PG quasars (dashed line) and (c) the average $\alpha_{\text{OX}}$ of X-ray selected quasars, according to Elvis et al. 1994 (bottom continuous line). The three low-luminosity objects are those with Chandra fluxes significantly higher than ROSAT upper limits.