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The X-ray emission from broad absorption line quasars

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Abstract. Pointed ASCA observations as well as archival ROSAT data are used for a study of the X-ray emission of the three BAL Quasars LBQS 2212-1759, PG 1411+442, and PG 0043+039. All three objects are found to be X-ray quiet, possibly due to substantial intrinsic absorption with $N_H > 10^{23}\,\mathrm{cm}^{-2}$ but might have intrinsically a more typical spectral energy distribution. This picture is supported by explicit spectral fits to the combined ROSAT/ASCA data of the nearby bright object PG 1411+442. An analysis of the large number of radio-quiet quasars not detected in the ROSAT All-Sky Survey indicates that perhaps only a small fraction of BAL quasars have not been recognized before and that the number of intrinsically X-ray quiet quasars must be small.

Key words: X-rays: galaxies – galaxies: quasars: general – galaxies: active

1. Introduction

About 10–15% of optically selected QSOs have optical/UV spectra showing deep, wide absorption troughs, extending up to $\Delta v \sim$ 0.1–0.2c, displaced to the blue of their corresponding emission lines. These Broad Absorption Line quasars (BALQSOs) show absorption features due to high ionization lines of C^{+3}, Si^{+3}, N^{+4}, O^{+3} and other lines. Lower ionization broad absorption lines of Mg II and Al III are seen in $\sim$ 10% of optically selected BALQSOs. Aside from the absorption lines themselves, the spectra of BALQSOs are very similar to those of ordinary quasars.

BALQSOs are generally found only among the radio quiet population (Stocke et al. 1992) although Francis et al. (1993) point out that the radio-loud end of radio-quiet quasars (the so called 'radio moderate' quasars) contains a relatively large fraction of BALQSOs. Only recently, the first radio-loud BALQSOs have been found (Becker et al. 1997, Brotherton et al. 1998). The BAL phenomenon is suspected to result from a line of sight passing through highly ionized, high column density (log $N_H > 20\,\mathrm{cm}^{-2}$) absorbers, flowing outward from the nuclear region with high velocities. Recent work suggests that BALQSOs are normal, radio quiet quasars (RQQ) seen from an unusual direction (Weyman et al. 1991, Hamann et al. 1993), i.e., orientation is indeed the cause of the BAL phenomenon and all radio-quiet QSOs have BAL regions. From a statistical study of the polarization distribution of radio-quiet quasars Goodrich (1997) deduces that a fraction of at least 30% of the objects exhibits the BAL phenomenon.

The standard model for broad-line emission assumes that many clouds, which are (3–30)$\times 10^{17}$ cm from the central source, intercept 10% of the ionizing radiation and re–radiate it in emission lines. There are numerous well-known problems with the cloud model of which most can be overcome by the disk wind picture (Murray et al. 1995). In that model the line-emitting gas emerges from the disk, there is no cloud confinement problem, the wind naturally produces the smooth line profiles and the covering fraction of the wind is 10%, which explains the observed fraction of BAL quasars.

Thus, BALQSOs provide a unique probe of conditions near the nucleus of most QSOs. Still, the geometry, covering factor, temperature, density, metallicity and ionization parameter of the absorbing material are poorly understood from optical/UV absorption line studies (Lanzetta et al. 1991). X-ray data, i.e., the amount of absorption, the depth and position of absorption edges – and the simultaneous exploitation of the UV and X-ray spectra (Marthur et al. 1994) could provide important constraints for the physically allowed parameter ranges of the BAL material.

Until recently, the X-ray properties of BALQSOs as a class were unknown. Green et al. (1995) investigated a sample of 36 BALQSOs uniformly selected from the 908 QSOs observed during the ROSAT All Sky Survey (RASS) in the LBQS sample (Hewett et al. 1995) and found that the average number of PSPC counts was lower than the corresponding number for comparison samples. This implies that the objects are either highly absorbed, intrinsically under-luminous in X-rays, or both. The great similarity of the optical/UV emission lines in BAL and non-BAL QSOs and the known optical/UV absorption, however, strongly argues for strong absorption as the likely explanation for the paucity of BALQSO detections in soft X-rays.

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In a study of BALQSOs from publicly available data of deep pointed ROSAT observations Green & Marthur (1996) mainly found upper limits for the sources. One of the two objects detected in soft X-rays seems not to be a bona fide BALQSO (PG 1416-129), while the second (1246-057) was detected marginally in a 57 ksec observation with an intrinsic column of 1.2×10^{23} cm^{-2}. Marthur et al. (1996) have observed the BALQSO PHL5200 with ASCA and found it to be strongly intrinsically absorbed ($N_H \sim 10^{23}$ cm^{-2}). As it is rather distant (z = 1.98) only a total of $\sim$ 1000 counts were collected in all four instruments which inhibited a detailed spectral analysis. However, the object is the prototype of a small subgroup of BALQSOs showing deep absorption with relatively low radial velocities (Turnshek et al. 1988, Goodrich 1997) and is radio-loud.

These observations further support the idea that BALQSOs are not intrinsically X-ray faint but heavily absorbed and thus hard to detect in ROSAT's soft energy band. In the optical–to–X-ray regime the spectral energy distribution of radio-quiet quasars is commonly characterized by its X-ray loudness α_{ox}, i.e., the broad band spectral index between 2500 Å and 2 keV, defined as $\alpha_{ox} = -0.384\, log(L_{2\,keV}/L_{2500\,\text{Å}})$. Various studies of different radio-quiet quasar samples derived average values of 1.4 $\lesssim \langle\alpha_{ox}\rangle \lesssim$ 1.65 (Zamorani et al. 1981, Tananbaum et al. 1986, Wilkes et al. 1994, Green et al. 1995, Yuan et al. 1998a). The average X-ray loudness appears to be independent of redshift, i.e., the luminosity ratio does not show cosmological evolution, and a previously claimed dependence on optical luminosity can be attributed to selection biases and the intrinsic dispersion of the luminosity distributions (Yuan et al. 1998b).

Quasars with $\alpha_{ox} \gtrsim$ 1.8 must be regarded as 'X-ray quiet' and, as a matter of fact, the ROSAT upper limits for the BALQSOs studied by Green & Marthur (1996) result in values $>$ 1.8. The existence of objects with *intrinsic* α_{ox} substantially larger than the above average values for radio-quiet quasars would indicate the presence of a second, intrinsically X-ray quiet population of quasars undetectable in ROSAT's soft energy band. ASCA with its wide energy range is currently the only instrument capable to test this scenario against the intrinsic absorption hypothesis and to study the matter distribution, its ionization status and abundances, as well as the geometrical conditions in the central regions of quasars.

We will present here the results of ASCA observations of three BALQSOs. LBQS 2212-1759, at a redshift of z=2.217 and an apparent magnitude of B_J = 17.94, was the only object which was claimed to be seen in the ROSAT Survey (Green et al. 1995), however at a low statistical significance. Its X-ray loudness was given as α_{ox} = 1.28, which is a rather low value for a radio-quiet quasar, i.e., the object would be unusually X-ray bright. The second object, PG 1411+442, is a nearby (z = 0.0896) very bright (m_v = 14.99) quasar which was already detected in a deep ROSAT PSPC observation (Rachen et al. 1996). The third, PG 0043+039, is a m_v = 15.88 mag BAL quasar at a moderate distance of z = 0.385. It shows extremely strong optical Fe II emission and a peculiar UV spectrum (Marziani et al. 1996). The object has not been detected by ROSAT.

2. The X-ray data

2.1. LBQS 2212-1759

2.1.1. The ASCA observation

LBQS 2212-1759 was observed with ASCA (Tanaka et al. 1994) on November 29, 1997 for a total of $\sim$ 68 ksec. Both Solid state Imaging Spectrometers, SIS-0 and SIS-1 were operated in 1-CCD Faint mode, and both Gas Imaging Spectrometers GIS-2 and GIS-3 were in normal PH mode. The source center was placed at the so-called "1 CCD nominal position", which is near the center of SIS-0 chip 1 and SIS-1 chip 3. All data used were selected from intervals of high and medium bit rate. After applying the standard screening criteria for the data the remaining net exposure time was $\sim$ 27.7 ksec for each GIS and $\sim$ 28 ksec for the SIS.

No obvious signal at the position of the source was found, neither in the SIS nor in the GIS detectors. We counted the photons in circles with different radii centered on the source position and found that the number of counts is directly proportional to the encircled area; i.e., there is no statistically significant excess flux at the source position. Therefore, we summed up the number of photons inside a circle of 4 arcmin radius centered on the source position, which is the typical extraction radius for weak sources in the GIS, and obtained 563 counts from both detectors. Taking the standard deviation of these counts, divided by the total exposure of 55320 sec we obtain a value of 1.3×10^{-3} cts/s as 3σ upper limit to the source count rate in the GIS.

A similar estimate, using an extraction radius of 3 arcmin, results in a SIS 3σ upper limit of 1.2×10^{-3} cts/s.

From these upper limits to the count rates we determine upper limits for the 2–10 keV X-ray flux, assuming a simple power law with photon index $\Gamma = 1.8$, typical for radio-quiet quasars in the ASCA band and Galactic absorption towards the source. The upper limit for the GIS is $f_{GIS} \leq 3.3 \times 10^{-14}$ erg cm$^{-2}\, s^{-1}$, for the SIS we get $f_{SIS} \leq 2.4 \times 10^{-14}$ erg cm$^{-2}\, s^{-1}$.

With the upper limit from the SIS we obtain an upper limit to the monochromatic, K-corrected 2 keV intrinsic luminosity of 1.0×10^{27} erg s^{-1}Hz^{-1}. For the K-correction of the optical luminosity we use an energy index of $\alpha = 0.5$. The resulting lower limit for the X-ray loudness from the ASCA data is then $\alpha_{ox} \gtrsim$ 1.74.

2.1.2. The ROSAT observation

LBQS 2212-1759 was in the PSPC field of view of a $\sim$ 10 ksec pointing on the source RX J2213.0-1710 (ROR 701191p), performed on May 31, 1993. The source position was near the outer rim of the detector, at a distance of $\sim$ 0.83 degrees from the axis and thus heavily affected by the blurring of the telescope. No obvious source is visible at the position of the quasar.

We determined an upper limit for the flux from LBQS 2212-1759 by using standard routines within the *EXSAS* environment (Zimmermann et al. 1994). The procedure uses a maximum-likelihood source detection algorithm and returns the 3σ upper limit on the number of source photons within 5 times the FWHM of the PSPC's point spread function, which was taken to be $\sim$ 60 arcsec, appropriate at this outer position of the detector. We estimated the local background by taking the average of two source free boxes near the quasar position. The resulting count rates were calculated with the vignetting-corrected exposure averaged over a 5 arcmin circle centered on the source position. The corresponding un-absorbed flux was determined using the energy-to-counts conversion factor *(ECF)* (ROSAT AO-2, technical appendix, 1991) assuming a simple power law with photon index $\Gamma = 1.8$ and Galactic absorption. The thus obtained upper limit to the 0.1–2.4 keV flux is $f_{rosat} = 1.27 \times 10^{-13}$ erg $\text{cm}^{-2}\,s^{-1}$.

This flux limit results in an upper limit for the monochromatic 2 keV source luminosity of $\sim 4.1 \times 10^{27}$ erg $\text{s}^{-1}\text{Hz}^{-1}$, a value considerably less stringent than that obtained from the deeper ASCA observation.

2.2. PG 1411+442

2.2.1. The ROSAT observation

The object was observed with ROSAT in June 1991 for $\gtrsim 25$ ksec (Rachen et al. 1996) and a total of 926$\pm$32 net counts were detected from the source. The spectrum in the soft X-ray band appears to be steep (photon index $\Gamma = 3.19 \pm 0.20$) and the fitted absorption is compatible with the Galactic value. The apparent X-ray loudness deduced from this measurement is α_{ox} $\sim$ 2.31. The unusually steep X-ray slope inhibits, however, an unambiguous physical interpretation of this value.

2.2.2. The ASCA observation

PG 1411+442 was observed by ASCA on December 8, 1996 for a total of $\sim$ 40 ksec. After applying the standard selection criteria to the data we obtained a net exposure for the SIS of $\sim$ 36 ksec, for each GIS detector we got $\sim$ 35 ksec.

The total number of photons extracted for the source for the two SIS detectors is about 590, for the two GIS detectors about 390. The low photon statistics inhibited any detailed spectral analysis. As the SIS and GIS spectra are consistent with each other, both the SIS data (0.5–10 keV) and the GIS data (0.7–10 keV) were fitted simultaneously. Further, for spectra with statistics as poor as these, the statistical uncertainty exceeds the calibration uncertainties, which can amount up to 20% at energies below 1 keV. As a check we have compared the results from spectral fits excluding or including the least reliably calibrated part of the SIS spectral band, 0.5–0.65 keV; the results are essentially the same. We also checked the possible effects of the non-uniform charge transfer inefficiency of the SIS by manually offsetting the gain up to 20 eV (gain command in XSPEC); no significant change in the fitting parameters was found.

A simple power law fit yielded a photon index of $\Gamma = -0.2 \pm 0.2$, however, formally unacceptable with large systematic positive residuals at low and high energies. This spectral slope is considerably flatter than the steep ROSAT spectrum. Fitting the ASCA spectrum at energies below 2 keV only, we find a similar steep power law slope and normalization as in the ROSAT data while an ASCA fit to the higher energy data gives a power law slope typical for quasars (see Table 1). Adding a narrow Fe K_α line ($\sigma = 0.01$) to the model yields an upper limit for the equivalent width of the line of 210 eV.

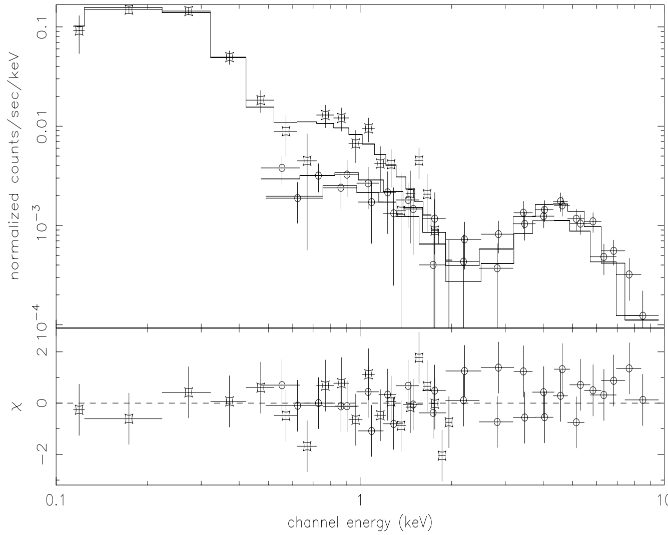

Fig. 1. Joint fit of the combined ROSAT–ASCA data to PG 1411+442. For clarity only the ROSAT–SIS data are plotted. The upper panel shows the model (full line), the ROSAT data points (open squares) and the ASCA points (open circles). The bottom panel gives the residuals of the fit (see text).

Therefore, we combined the ASCA and ROSAT data and performed a joint fit. The best fits were obtained by using an intrinsically absorbed (zwabs–model in XSPEC) power law model plus a low energy power law with Galactic absorption.

Fig. 1 shows the best joint ROSAT–SIS fit. In the upper panel the full line represents the model, open squares are the ROSAT data, open circles the ASCA data points. The bottom panel shows the residuals of the fit. The best fit parameters obtained are $\Gamma_{low} = 3.07 \pm 0.12$, $N_{H\ high} = (2.4 \pm 0.5) \times 10^{23}\,\text{cm}^{-2}$; the value for Γ_{high} was fixed to be 2.0 (errors are at the 2.7σ level). The reduced χ^2 of this fit was $\chi^2_{red}/\nu = 1.0/80$. The large intrinsic N_H is in accordance with the similar result found for PHL 5200 (Marthur et al. 1996). At low energies we find an extra soft component which can be interpreted as scattered primary radiation. The flux of this component at 1 keV is about 5% of the un-absorbed hard flux.

With the observed X-ray flux at 2 keV we deduce from the data an X-ray loudness of $\alpha_{ox,obs} \sim 2.2$, however, if we take the intrinsic, un-absorbed flux from the hard power law we obtain a value of $\alpha_{ox,intr} \sim 1.6$ which is is similar to the average $\langle\alpha_{ox}\rangle$ of radio-quiet quasars.

2.3. PG 0043+039

We retrieved the data for this object from the public ASCA archive. The observation took place on December 21, 1996.

Table 1. Summary of ROSAT and ASCA spectral fits

Data	Model	$N_H^{(1)}$	$\Gamma^{(1)}$	$N_0^{(1)}$	$N_H^{(2)}$	$\Gamma^{(2)}$	$N_0^{(2)}$	χ^2/ν
ROSAT	wabs$^{(1)}$*pl$^{(1)}$	0.014(f)	$3.08^{+0.16}_{-0.15}$	0.38				16/17
ASCA <2.4 keV	wabs$^{(1)}$*pl$^{(1)}$	0.014(f)	$3.14^{+0.85}_{-0.85}$	0.42				34/27
ASCA >2 keV	wabs$^{(1)}$*zwabs$^{(2)}$*pl$^{(1)}$	0.014(f)	$1.6^{+0.8}_{-0.7}$	4.11	15^{+13}_{-6}			26/34
ASCA	wabs$^{(1)}$*pl$^{(1)}$	$0.0^{+0.11}$	$-0.2^{+0.2}_{-0.2}$	1.07				115/62
ASCA	wabs$^{(1)}$(zwabs$^{(2)}$*pl$^{(1)}$+pl$^{(2)}$)	0.014(f)	2.0(f)	8.83	24^{+5}_{-5}	$3.05^{-0.63}_{-0.71}$	0.40	63/61
ASCA+ROSAT	wabs$^{(1)}$(zwabs$^{(2)}$*pl$^{(1)}$+pl$^{(2)}$)	0.014(f)	2.0(f)	8.90	24^{+5}_{-5}	$3.07^{+0.12}_{-0.12}$	0.40	80/80

Notes: N_H values in units of 10^{22} cm^{-2}
Normalization N_0 at 1 keV in units of 10^{-4} photons keV^{-1} cm^{-2} s^{-1}
(f) indicates that the parameter is fixed

The net exposure after screening for this source was $\sim$ 26.8 ksec for the GIS and $\sim$26.1 ksec for the SIS.

No source was found at the quasar position. Applying the same procedure as for LBQS 2212+1759 we obtain 3σ upper limits for the 2–10 keV flux of $f_{GIS} = 3.0 \times 10^{-14}$ erg cm^{-2} s^{-1} and for the SIS $f_{SIS} = 1.8 \times 10^{-14}$ erg cm^{-2} s^{-1}, respectively. This SIS upper limit corresponds to a monochromatic, K-corrected 2 keV intrinsic luminosity limit of 2.0×10^{25} erg s^{-1}Hz^{-1}, resulting in a lower limit for the X-ray loudness from the ASCA data of $\alpha_{ox} \gtrsim 2.2$.

3. X-ray detection of radio-quiet quasars

As mentioned above the weakness of the X-ray flux from BALQSO seems to be related to the fact that the emission regions are seen through heavy attenuation (Goodrich 1998), otherwise they appear to be quite normal RQQ. Further, BAL regions seem to be common to radio-quiet quasars but the real fraction of BALQSO to the quasar population is still uncertain. Thus, the probability to detect a RQQ in X-rays must depend on its orientation, i.e., the extent of the BAL region and/or the anisotropy of the X-ray emission. Therefore, the large number of quasars not detected in the ROSAT survey might partly be a large population of unrecognized BAL quasars.

To test the possibilities for measuring this orientation effect and to examine the fraction of truly X-ray quiet radio-quiet quasars we investigated the $\sim$ 4800 RQQ of the 6th Véron-Cetty & Véron (1993) quasar catalogue which were not detected in the ROSAT Survey (for details see Yuan et al. 1998a). If all quasars would form a homogeneous class with similar α_{ox} the expected (intrinsic) X-ray luminosity of each object can be calculated from the optical luminosity for a specific X-ray loudness α_{ox}. This value is then converted into to a soft (0.1–2.4 keV) soft X-ray flux by assuming a spectral photon index of $\Gamma = 1.8$ for the K-correction.

For the detection of a quasar in the ROSAT Survey with a likelihood $M_L \geq 10$ on average a minimum of about 10–12 photons was needed (Yuan 1998, see Fig. 1 of Brinkmann et al. 1997). However, this limit is not very strict and depends on the actual exposure, the background, and the photon distribution (Cruddace et al. 1988). From the ROSAT Survey exposure of the quasar position we determine the minimum count rate for a

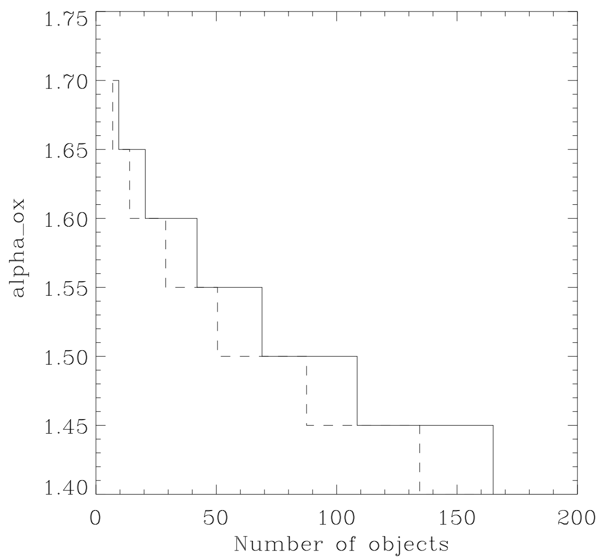

Fig. 2. The number of quasars detectable in the RASS as function of a common intrinsic X-ray loudness α_{ox} in excess of the true number of RASS detections. The dashed line represents the detection limit of a total of 12 counts from the source, the full line is for the 10 counts limit (see text).

source detection for both values of 10 or 12 counts as detection minimum. The corresponding flux limits are then obtained by converting these count rates into soft 0.1–2.4 keV X-ray fluxes via the *ECF*, using Galactic absorption towards the sources and the redshift dependent photon index for radio-quiet quasars, as given by Yuan (1998). If the source flux estimated from the given α_{ox} is higher than this detection threshold we regard the quasar as being detectable in the RASS. The ratio of these additionally 'detectable' quasars and the actually detected objects will thus be a measure of the fraction of quasars hidden by their BAL regions – if all quasars have the same α_{ox}.

In Fig. 2 we plot the number of RQQ which should have been detected in addition to the 461 objects in the All-Sky Survey as a function of a hypothetical universal value of α_{ox}. The dashed line represents a photon number limit of 12 counts, the full line 10 counts. It can be seen that for reasonable values of the X-ray loudness α_{ox} (the conventional mean for the ROSAT RQQ sample is $\langle\alpha_{ox}\rangle = 1.54 \pm 0.01$, Yuan et al. 1998a), this number is only a relatively small fraction of the detections. Even at higher $\alpha_{ox} \gtrsim 1.65$ a small number of undetected objects should have been seen in the Survey. It turns out that most of them are, in some sense, peculiar with unreliable parameters.

For a more detailed analysis the internal dispersion of the α_{ox} has to be considered and the effects of the quasars temporal variability must be taken into account which is, however, in RQQ much more moderate than in their radio-loud equivalents. Finally, we have used relatively conservative lower limits for the detectable source counts, based on a likelihood for existence of $M_L \geq 10$, corresponding to $\sim 4\,\sigma$, used for the source detection in the RASS II processing (Voges et al. 1996). But Fig. 2 clearly demonstrates that even a substantial relaxation of the detection limits will not result in a considerable increase of the number of detectable sources.

4. Conclusions

We have presented deep ASCA and ROSAT observations of three BAL quasars. Only upper limits could be given for two of the objects (LBQS 2212-1759 and PG 0043+039) and thus the reported detection of LBQS 2212-1759 in the ROSAT All-Sky Survey is questionable. The nearby and optically very bright object PG 1411+442 allowed a limited spectral fit, which is consistent over the wide ROSAT–ASCA energy band. The interpretation of the soft emission component in PG 1411+442 as scattered flux is in accordance with the idea that the high polarization of P $\geq$ 3% found in a relatively large fraction of BALQSO is caused by scattering inside the BAL region (Goodrich 1997). In addition, the fact that the ROSAT photon index in PG 1411+442 follows the well known Γ–FWHM(H_β) relation (see Fig. 6 of Wang et al. 1996) suggests that we see an attenuated intrinsic X-ray spectrum in the ROSAT band. This is also consistent with the scattering interpretation.

Although there are strong indications that the X-ray weakness in the objects is caused by strong intrinsic absorption with $N_H > 10^{23}\,\mathrm{cm}^{-2}$ column densities a clear detection of high energy X-ray photons is crucial for an unambiguous confirmation of the absorption scenario. Both, the upper limits and the detections demonstrate that the value of the apparent X-ray loudness α_{ox} of BALQSO is high, ~ 2. However, before absorption the intrinsic value seems to be compatible with that of normal RQQ, $\alpha_{ox} \lesssim 1.6$, supporting the idea that this class of objects in fact consists of principally normal radio-quiet quasars, possibly seen close to their equatorial plane.

The results are in agreement with previous attempts to find in the soft ROSAT energy band X-ray emission from BALQSOs which generally yielded only upper limits (Green & Marthur 1996) with values $\alpha_{ox} > 1.8$, from which intrinsic absorption column densities of $N_H > few \times 10^{22}\,\mathrm{cm}^{-2}$ were inferred, assuming that the X-ray 'weakness' is caused by absorption in the source. ASCA's wider energy band should, in principle, allow to narrow down these values. In fact, if we assume an intrinsic α_{ox} = 1.6 and a power law with $\Gamma = 1.8$ for the objects, the column density for the obtained upper limits would be $N_{H,z} > 5.5 \times 10^{23}\,\mathrm{cm}^{-2}$ for PG 0043+039 and $N_{H,z} > 6 \times 10^{21}\,\mathrm{cm}^{-2}$ for LBQS 2212-1758, where the latter value is not well constrained. Analogous results were obtained by Gallagher et al. (1999) for PG 0043+039 in a similar study of ASCA BAL quasars. The two definite X-ray detections, the nearby bright object PG 1411+442, and PHL 5200 are perhaps indicators for the existence of slightly distinct subclasses in the BAL quasar population.

A study of the population of RQQ which remained undetected in the ROSAT Survey indicates that only a small fraction of them can have failed a detection due to their currently unrecognized BAL properties. For the majority of the sources the survey was just too shallow. This sensitivity argument holds as well for most of the known BALQSOs: they would not have been detected even if they were not intrinsically obscured. Finally, the analysis does not support the idea that there exists a class of X-ray weak radio-quiet quasars with intrinsic $\alpha_{ox} \gtrsim 2$.

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