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THOMSON THICK X-RAY ABSORPTION IN A BROAD ABSORPTION LINE QUASAR, PG 0946+301

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ABSTRACT

We present a deep *ASCA* observation of a broad absorption line quasar (BALQSO) PG 0946+301. The source was clearly detected in one of the gas imaging spectrometers, but not in any other detector. If BALQSOs have intrinsic X-ray spectra similar to normal radio-quiet quasars, our observations imply that there is Thomson thick X-ray absorption ($N_{\rm H} \gtrsim 10^{24}$ cm^{-2}) toward PG 0946+301. This is the largest column density estimated so far toward a BALQSO. The absorber must be at least partially ionized and may be responsible for attenuation in the optical and UV. If the Thomson optical depth toward BALQSOs is close to 1, as inferred here, then spectroscopy in hard X-rays with large telescopes like *XMM* would be feasible.

Subject headings: galaxies: active — quasars: absorption lines — quasars: individual (PG 0946+301) — X-rays: galaxies

1. INTRODUCTION

About 10%–15% of optically selected QSOs have optical/UV spectra showing deep absorption troughs displaced blueward from the corresponding emission lines. These broad absorption lines (BALs) are commonly attributed to material flowing toward the observer with velocities of up to ∼50,000 km s^{-1}. Broad absorption line quasars (BALQSOs) are probably normal QSOs viewed at a fortuitous orientation passing through a BAL outflow, thus implying a BAL "covering factor" at least 10%–15% in all QSOs. BALQSOs thus provide a unique probe of conditions near the nucleus of most QSOs. The absorbing columns typically inferred from the UV spectra for the BAL clouds themselves are $N_{\rm H} \sim 10^{20}$–10^{21} cm^{-2} (Korista et al. 1993). It has been noted, however, that UV studies underestimate the BAL column densities because of saturation (Korista et al. 1993; Arav 1997; Hamann 1998). BALQSOs, as a class, show higher optical/UV polarization than other radio-quiet QSOs (Schmidt & Hines 1999; Ogle et al. 1999). Polarization studies reveal multiple lines of sight through high column density gas (Goodrich & Miller 1995; Cohen et al. 1995).

With the absorbing column densities as estimated from the earlier UV studies, we would have expected very little soft X-ray absorption in the BALQSOs. However, BALQSOs are found to be markedly underluminous in X-rays compared to their non-BALQSO counterparts (Bregman 1984; Singh, Westergaard, & Schnopper 1987; Green et al. 1995). Green & Mathur (1996, hereafter GM96) studied 11 BALQSOs observed with *ROSAT* and found that just one was detected with $\alpha_{\rm ox}$[15] about 2. BALQSOs thus have unusually weak soft X-ray emission, as evidenced by large $\alpha_{\rm ox}$ ($\gtrsim$1.9 compared to $\alpha_{\rm ox} = 1.51 \pm 0.01$ [from Laor et al. 1997] for radio-quiet quasars). If BALQSOs are indeed normal radio-quiet QSOs, then their weak X-ray flux is most likely due to strong absorption. Unfortunately, due to the low observed flux, there are no observed X-ray spectra of BALQSOs to confirm the absorption scenario, with one exception: the archetype BALQSO PHL 5200 (Mathur, Elvis, & Singh 1995a). The *ASCA* spectrum of PHL 5200 is best fit by a power law typical for non-BALQSOs in the 2–10 keV range, with intrinsic absorption 2–3 orders of magnitude higher than inferred from UV spectra alone (Mathur et al. 1995a). However, the PHL 5200 spectrum suffers from a low signal-to-noise ratio, and while the above was a preferred fit, a model with no intrinsic absorption also fits the data. Recently Gallagher et al. (1999, hereafter G99) studied a sample of six new BALQSOs with *ASCA*, of which two were detected. G99 derived column densities of $\gtrsim 5 \times 10^{23}$ cm^{-2} to explain the nondetections, even higher than the *ROSAT* estimates (assuming a neutral absorber with solar abundances unless stated otherwise).

How are the X-ray and UV absorbers related to each other? Are they both part of the same outflow? If so, then the kinetic energy carried out is a significant fraction of the bolometric luminosity of the quasar (see Mathur, Elvis, & Wilkes 1995b for a discussion). With all QSOs likely to contain a BAL outflow, it becomes very important to measure the absorbing column density accurately to understand the energetics and dynamics of quasars. We attempt this with a deep *ASCA* observation of a typical BALQSO, PG 0946+301.

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[15] The slope of a hypothetical power law connecting 2500 Å and 2 keV is defined as $\alpha_{\rm ox} = 0.384 \log L_{\rm o}/L_{\rm x}$, so that $\alpha_{\rm ox}$ is larger for objects with weaker X-ray emission relative to optical.

TABLE 1
ASCA COUNT RATES FOR PG 0946+301

Background	SIS0	SIS0 Hard	SIS1	GIS2	GIS3	GIS3 Hard
Background 1[a] ……	0.855 (2 σ), <1.2	<0.74	<1.2	<0.75	1.84 (7.9 σ)	1.4 (8.7 σ)
Background 2[b] ……	1.29 (3 σ)	0.51 (2 σ), <0.74	<1.2	<0.75	0.52 (2 σ), <0.83	0.48 (2 σ), <0.63

NOTE.—Values are given in units of 10^{-3} photons s^{-1}. The significance of detection is given in parentheses. For nondetections, the 3 σ upper limit is given. For 2 σ detections, the 3 σ upper limit is listed as well. For SIS0 and GIS3, hard band count rates are listed as well.

[a] With background from a source-free region on the detector.

[b] With background from blank sky observations.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. *Observations*

We observed PG 0946+301 with *ASCA* (Tanaka, Holt, & Inoue 1994) on 1998 November 12. *ASCA* contains two sets of two detectors: the solid-state imaging spectrometer (SIS) and the gas imaging spectrometer (GIS). The effective exposure times in SIS0, SIS1, GIS2, and GIS3 were 72,024, 69,668, 80,910, and 80,896 s, respectively. SIS was operated in 1 CCD mode with the target in the standard 1 CCD mode position. GIS was operated in pulse height mode. The data were reduced and analyzed using FTOOLS and XSELECT in a standard manner (see *ASCA* Data Reduction Guide or Mathur et al. 1995a and G99 for details of data reduction).

2.2. *Image Analysis*

2.2.1. *XSELECT Analysis*

We used XSELECT to create full and hard (2–9.5 keV) band images for each of the four detectors. We also created combined SIS and GIS images. We looked for the target in these images displayed with SAOIMAGE. While there were sources seen within the GIS field of view, there was no obvious source seen at the target position in any of the four detectors. We then smoothed the images with a Gaussian function of $\sigma = 1$–2 pixels. A faint source at the position of the target was then evident in the GIS3 hard-band image and a trace of a source was seen in the full GIS image, but not in any other image. Note that for a standard pointing position, the target lies closest to the optical axis in SIS0 and GIS3. GIS3 is more sensitive in hard X-rays than SIS0. The fact that the source is seen by eye in the GIS3 detector only suggests that the source is faint with flux mainly in the hard band.

We extracted the total counts in a circular region with a 3′ radius centered on the source position. Because our source is observed to be so faint, background subtraction is crucial in determining the net source count rate, so we have done careful background subtraction using different background estimates. Background counts were extracted in two different ways: (1) from a source-free region on the detector and (2) from exactly the same region as the source in the blank sky background files provided by the *ASCA* guest observer facility. The significance of the source detection was therefore different for different background estimates. For SIS, the blank sky background is underestimated because it is available in the BRIGHT mode only, while the source counts were extracted in the BRIGHT2 mode. So the SIS detections are less reliable with background 2. We found that the source was detected in GIS3 and the GIS3 hard band and is marginally detected in SIS0 (2 σ). It was not detected in any other detector in either bandpass. The significance of detection for the source in different detectors and the resulting net count rate is given in Table 1. For nondetections, we give a 3 σ upper limit of the count rate (see G99 for exact formulation of the detection and corresponding count rate estimate).

2.2.2. *XIMAGE Analysis*

Determination of whether or not the source is detected is extremely important to our results. As an independent check, we performed image analysis with XIMAGE (Giommi, Angellini, & White 1997), which is designed for detailed image analysis. The DETECT algorithm in XIMAGE locates point sources in an image by means of a sliding-cell method. We used DETECT on all of our images and looked for a source at the position of the target. Again, we found the source to be detected in the GIS3 hard band. To minimize the number of spurious sources detected, the threshold used by DETECT is somewhat conservative. As a result, sources with intensity just above the image background can be missed. We found that the source was detected in the full band GIS image if we lowered the detection threshold. The source was not detected in other detectors. These results are consistent with those from the XSELECT analysis discussed above.

2.2.3. *CIAO Analysis*

We applied more sophisticated wavelet-based techniques (Freeman et al. 2000) to provide independent support to the above detections. Software developed for *Chandra* Interactive Analysis of Observations (CIAO) allows us to decompose the image such that structures at different scales are enhanced. We analyzed the central 20′ region of GIS3 images in both the full spectral range and in the harder range. Wavelet analysis of the GIS image at scales approximating the size of the point-spread function shows that detection of PG 0946+301 is complicated by the presence of a strong nearby source ∼5′ away. In the GIS hard band image, this source is significantly weaker, and we detect PG 0946+301 at a probability of spurious detection of 10^{-4}, with a net count rate of $(1.26 \pm 0.25) \times 10^{-3}$ counts s^{-1} (90% confidence). This is consistent with the results discussed above.

2.3. *Column Density Constraints*

Consistency among the methods discussed above gives us confidence in our measurements and in our resulting detections in GIS3 and nondetections in other detectors. If the low observed X-ray count rate is due to intrinsic absorption, we can estimate the absorbing column density in PG 0946+301. Since the source did not yield enough net counts in any detector to perform spectral analysis, we use the method discussed in GM96 to determine the column density. We first calculate the flux expected from the source if there was no intrinsic absorption. This was done using the observed B-magnitude of the source ($B = 16.0$ mag) and assuming $\alpha_{\rm ox} = 1.6$. The redshift of the source ($z = 1.216$) and the Galactic column density

TABLE 2

COLUMN DENSITY CONSTRAINTS

Detector	Γ	Detection[a]	3 σ Lower Limit[b]	2 σ Detection
GIS3	1.7	0.95	2.1	3.3
	2.0	0.52	1.2	1.95
GIS3 hard	1.7	1.2	2.55	3.2
	2.0	0.67	1.55	1.95
SIS0	1.7	1.4	1.42	1.95
	2.0	0.9	0.92	1.3
SIS0 hard	1.7	…	2.12	2.73
	2.0	…	1.42	1.86

NOTE.—Values are given in units of 10^{24} atoms cm^{-2}.

[a] If 3 σ or better detection (Table 1), either background. Note: the column densities derived here are lower than the 3 σ lower limits because the two are from two different background measurements; e.g., for GIS3, detections are with background 1, while the 2 σ detections and 3 σ lower limits are with background 2.

[b] The upper limit on count rate gives the lower limit on the column density. The 2 σ detections and 3 σ lower limits are with the same background.

($N_H = 1.6 \times 10^{20}$ atoms cm^{-2}; Murphy et al. 1996) were taken into account to predict the 2–10 keV flux in the observed band (=7.2×10^{-13} ergs s^{-1} cm^{-2}). An X-ray power-law slope with photon index $\Gamma = 1.7$ was used. We then entered this model into the X-ray spectral analysis software XSPEC (Arnaud 1996), with normalization consistent with the expected flux and simulated spectra using SIS and GIS response matrices. The response of the telescope and detectors was taken into account as well. The column density at the redshift of the source was an additional parameter used in the simulation. If there was no intrinsic absorption, then the predicted count rate was found to be typically an order of magnitude larger than the observed one. We then varied the value of the intrinsic absorption, keeping the normalization constant, until the predicted and observed column densities matched. The values of intrinsic column density estimated in this way are given in Table 2.

This estimate of N_H depends upon Γ and α_{ox}. Given the observed range of α_{ox} (§ 1), our adopted value of $\alpha_{ox} = 1.6$ gives conservative estimates of column densities. X-ray spectral slopes also vary among quasars. So we have estimated N_H for $\Gamma = 2.0$ as well as $\Gamma = 1.7$. Flatter spectra result in even higher derived column densities. As shown in Table 2, even the conservative estimate results in Thomson thick X-ray absorption in PG 0946+301, i.e., $N_H \gtrsim 10^{24}$ cm^{-2}. The column density estimates are consistent with the detection in GIS3 and nondetection in SIS0.

Alternatively, is it possible that PG 0946+301 (and BALQSOs in general) is intrinsically X-ray weak? Earlier work (GM96; G99) could not rule out this possibility. To test this, we estimated the observed SIS0 hard band count rate for flux consistent with detection in GIS3 hard band, but no intrinsic absorption. We find that the source would have been detected in the SIS0 hard band at greater than 8 σ significance (with $\Gamma = 1.7$; >7 σ with $\Gamma = 2.0$). So we conclude that the observed X-ray weakness of BALQSOs is due to absorption and not due to intrinsic weakness. We cannot, however, rule out the possibility that the source is intrinsically X-ray weak with an unusual spectral shape (turning up at around 10 keV, rest frame). It is also possible that the observed flux is only the scattered component, from a line of sight different from the absorbing material. This is unlikely in PG 0946+301, which is not strongly polarized (0.85 ± 0.14%; Schmidt & Hines 1999). However, if true, it again implies the existence of X-ray–thick matter along the direct line of sight.

3. DISCUSSION

We have clearly detected the quasar PG 0946+301 in our deep *ASCA* observation, and we infer that there is Thomson thick X-ray absorption ($N_H \gtrsim 10^{24}$ cm^{-2}) toward this BALQSO. The use of a detection, rather than upper limits, to determine the absorption is highly significant. In earlier work, GM96 and G99 had estimated absorbing column densities of a few times 10^{22} and 10^{23} cm^{-2}, respectively. However, these were based on nondetections only and hence yielded only lower limits to the column density. A detection provides a much stronger estimate.

Assuming that there is indeed Thomson thick matter covering the X-ray source, can we infer its ionization state? The X-ray absorber will cover the optical and UV continuum sources as well, at least partially. If the absorber is completely neutral, it will result in significant H I opacity, which is not observed (Arav et al. 1999). If the absorber is completely ionized, then the opacity due to Thomson scattering would be the same in the optical, UV, and X-rays (up to $m_e c^2$). Thus, this scenario by itself cannot account for the unusually large values of α_{ox}. If, on the other hand, the hydrogen is mostly ionized but there are still some hydrogen- and helium-like heavy elements, then photoelectric absorption would still be the dominant mechanism in X-rays. In the optical/UV, a Thomson opacity of 1 would result in attenuation by a factor of 2.7. Based on a statistical comparison of polarization properties of BALQSOs and unabsorbed, radio-quiet QSOs, Schmidt & Hines (1999; see also Goodrich 1997) inferred an attenuation factor of 2.4 ± 0.3 for BALQSOs. This is consistent with the attenuation inferred here for PG 0946+301. The X-ray absorber thus must be at least partially ionized and may be responsible for attenuation in the optical and UV.

While PG 0946+301 suffers significant attenuation along the line of sight, it is not highly polarized. This might be because the scattering medium is not present or well placed in PG 0946+301 to produce high polarization. The scattering region may be attenuated as much or more than the direct view. Alternatively, it might be a geometric effect in which a large part of the UV continuum is not covered by the X-ray absorber, so it is unattenuated. Whether the X-ray absorber has an ionization state overlapping the range of UV BALs and whether the outflow velocities are similar remain outstanding questions. It is possible that the X-ray absorber is stationary, at the base of winds producing BALs. The X-ray continuum source might be preferentially covered. X-ray spectroscopy is necessary to better probe the nuclear region in BALQSOs. For PG 0946+301, we predict about 0.015 counts s^{-1} with the *XMM* PN. A reasonable spectrum may be obtained in about 70 ks.

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