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SURPRISES FROM A DEEP *ASCA* SPECTRUM OF THE BROAD ABSORPTION LINE QUASAR PHL 5200

S. Mathur,[1,2] G. Matt,[3] P. J. Green,[2] M. Elvis,[2] and K. P. Singh[4]

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ABSTRACT

We present a deep (~85 ks) *ASCA* observation of the prototype broad absorption line quasar (BALQSO) PHL 5200. This is the best X-ray spectrum of a BALQSO yet. We find the following: (1) The source is not intrinsically X-ray weak. (2) The line-of-sight absorption is very strong, with $N_H = 5 \times 10^{23}$ cm^{-2}. (3) The absorber does not cover the source completely; the covering fraction is ≈90%. This is consistent with the large optical polarization observed in this source, implying multiple lines of sight. The most surprising result of this observation is that (4) the spectrum of this BALQSO is *not* exactly similar to other radio-quiet quasars. The hard X-ray spectrum of PHL 5200 is steep, with the power-law spectral index $\alpha \approx 1.5$. This is similar to the steepest hard X-ray slopes observed so far. At low redshifts, such steep slopes are observed in narrow-line Seyfert 1 (NLS1) galaxies, believed to be accreting at a high Eddington rate. This observation strengthens the analogy between BALQSOs and NLS1 galaxies and supports the hypothesis that BALQSOs represent an early evolutionary state of quasars. It is well accepted that the orientation to the line of sight determines the appearance of a quasar; age seems to play a significant role as well.

Subject headings: galaxies: active — quasars: absorption lines — quasars: individual (PHL 5200) — X-rays: galaxies

1. INTRODUCTION

Broad absorption line quasars (BALQSOs), in which the kinetic energy carried out in the absorbing outflow is a significant fraction of the bolometric luminosity of the quasar, offer a challenge to our understanding of the quasar energy budget (as suggested in Mathur, Elvis, & Wilkes 1995b; see also § 11.3 in Krolik 1999). At the same time, they also offer new insights into the nuclear structure of quasars (Ogle 1998; Elvis 2000). X-ray observations are important in this investigation as they offer precise measurements of absorbing column densities. Combined UV and X-ray analysis is a powerful tool to understand the physical conditions in the absorbing gas (Mathur, Wilkes, & Elvis 1998 and references there in). However, X-ray observations of BALQSOs have essentially resulted in nondetections (Green & Mathur 1996). While the available evidence clearly suggested that the observed X-ray weakness of BALQSOs is a result of strong X-ray absorption (Mathur et al. 2000 and references there in), in some objects absorption was not apparent (Gallagher et al. 1999). So the nature of X-ray weakness of BALQSOs and the column density of absorption, if any, could not be determined with certainty for the lack of a good X-ray spectrum.

PHL 5200, the prototype BALQSO at $z = 1.98$ (Burbidge 1968) was clearly detected in the *EXOSAT* medium-energy experiment but not by the low-energy experiment (Singh, Westergaard, & Schnopper 1987). To obtain consistency between medium- and low-energy experiments requires a column density of $\gtrsim 10^{22}$ cm^{-2} at the source. The detection of PHL 5200 with *EXOSAT* made it an excellent candidate for detailed spectral study in X-rays. A 1994 *ASCA* observation of PHL 5200 yielded the first X-ray spectrum of a BALQSO (Mathur, Elvis, & Singh 1995a, hereafter MES95) and remained the only one until this year. However, the quality of the *ASCA* spectrum was poor, and the parameters of the fit were not well determined in the 17.7 ks observation. The photon index of the best-fit power law was uncertain to ± 0.9 (all the errors are quoted to 90% confidence, unless noted otherwise). While excess absorption with $N_H = 1.3^{+2.3}_{-1.1} \times 10^{23}$ cm^{-2} at the source provided a better fit, a model with only Galactic absorption was acceptable (see also Gallagher et al. 1999). A good signal-to-noise ratio spectrum of a BALQSO was very much needed, and PHL 5200 remained the best target. So we reobserved PHL 5200 with *ASCA*, to obtain better quality data and better constrain the parameters of an X-ray spectrum of a BALQSO. We find that the spectrum contains more surprises that affect the interpretation of the BAL phenomenon.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. *Observations*

We observed PHL 5200 with *ASCA* (Tanaka, Holt, & Inoue 1994) on 1999 November 21. *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 83,522, 73,320, 93,385, and 93,337 s, respectively. The SIS was operated in 1CCD mode with the target in the standard 1CCD mode position. The GIS was operated in pulse-height mode. The data were reduced and analyzed using FTOOLS and XSELECT in a standard manner (see the *ASCA* Data Reduction Guide for details of data reduction).

2.2. *Data Analysis*

The source was clearly detected in all four instruments with background-subtracted net count rates of $(8.6 \pm 0.5) \times 10^{-3}$, $(4.8 \pm 0.4) \times 10^{-3}$, $(5.6 \pm 0.6) \times 10^{-3}$, and $(10.9 \pm 0.6) \times 10^{-3}$ for SIS0, SIS1, GIS2, and GIS3, respectively. We extracted the source spectrum from a circular region centered on the source. For GIS2 and GIS3 we used the recommended 6′ radius. For SIS0 and SIS1 we used 3′ and 2′ radii, respectively.

[1] Astronomy Department, Ohio State University, 140 West 18th Avenue, Columbus, OH 43210-1173; smita@astronomy.ohio-state.edu.

[2] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.

[3] Departimento di Fisica, Universitá degli Studi Roma Tre, Via della Vasca Navale 84, 1-00146 Roma, Italy.

[4] Department of Astronomy and Astrophysics, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai, 400 005, India.

TABLE 1

Spectral Fits to *ASCA* Data of PHL 5200

Model	α_E	N_H(free)[a]	Additional Parameter	χ^2 (dof)
Power law + N_H (Galactic) fixed	0.5 ± 0.1	…	…	226.5 (137)
Power law + N_H (Galactic) fixed + N_H (z = 1.98)	$0.9^{+0.2}_{-0.3}$	8^{+4}_{-5}	…	212.5 (136)
Power law + partially covering absorber	1.78 ± 0.4	50 ± 14	Covering fraction = $0.90^{+0.05}_{-0.06}$	182.5 (135)
Power law + partially covering absorber, with Compton scattering	1.9 ± 0.4	62^{+19}_{-17}	Covering fraction = $0.94^{+0.03}_{-0.06}$	162.8 (132)
Power law + partially covering absorber + high-energy cutoff	1.4 ± 0.4	46^{+16}_{-17}	Covering fraction = $0.85^{+0.07}_{-0.14}$	157.3 (133)
	…	…	Cutoff energy = $18.0^{+0.4}_{-1.0}$	…

[a] In units of 10^{22} cm^{-2}.

Larger regions were not possible, as the source was quite close to the chip gap. Background events were extracted from the identical regions for each instrument from the deep background images supplied by the *ASCA* guest observer facility. For the GIS, the latest (1995 March) response matrices were used, while for the SIS, they were generated using FTOOL "SISRMG." The spectra were then corrected for vignetting, and the channels were grouped to contain at least 15 net counts per channel. In summary, the spectra for all instruments were extracted in a standard manner.

We also extracted background from different source-free regions on the same detector from our PHL 5200 observation. We found that the spectra extracted in this way did not alter our results in any significant way. For the rest of the Letter we will discuss only the spectra with background extracted from the deep background observations.

Our observations were taken toward the end of the *ASCA* mission, and the CCDs on the satellite were significantly degraded over time. There are problems with the charge transfer inefficiency, the residual dark distribution, and an unidentified additional loss of SIS low-energy efficiency.[5] For our observation in the 1CCD mode and for a weak source like PHL 5200, the latter is the most serious issue. The loss of the low-energy response of the two SIS detectors can be parameterized with excess absorption (Yaqoob et al. 2000). This "N_H correction" is different for SIS0 and SIS1 and is a function of time.

[5] For *ASCA* calibration uncertainties see http://legacy.gsfc.nasa.gov/docs/asca/cal_probs.html.

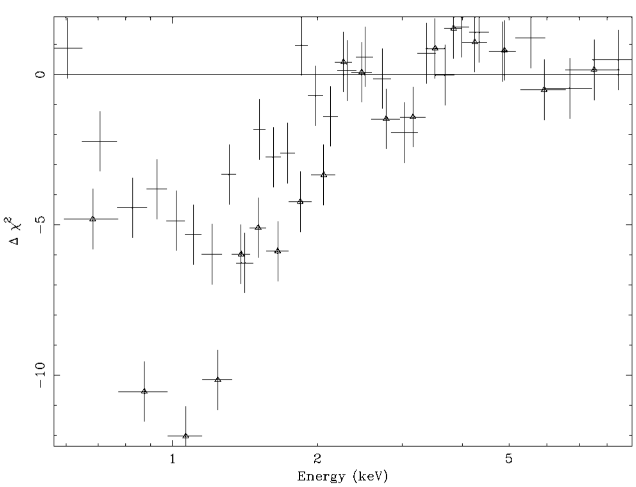

Fig. 1.—Residuals ($\Delta\chi^2$) to a power-law fit showing clear signature of a partially covering absorber. Here the power law was fitted to only the data above 2 keV and extrapolated to lower energies. Note the strong turnover below 2 keV and recovery below about 1 keV. Only SIS data are shown for clarity. *Dots*: SIS0; *triangles*: SIS1.

We have taken into account all the calibration uncertainties carefully in our spectral extraction and analysis.

2.3. *Spectral Analysis*

The extracted spectra were analyzed using XSPEC version 11.0 (Arnaud 1996). Data below 0.6 keV for the SIS, below 0.9 keV for the GIS, and above 9.5 keV for all the instruments were ignored in spectral fits, as these energy channels are not well calibrated. We first fitted the spectra from each instrument separately and found the results to be generally consistent. We then fitted all the spectra simultaneously leaving the normalizations free, to allow for small differences in absolute calibration (see Table 1).

As a first step we fitted the spectra with a simple power law and Galactic absorption (with $N_H = 4.8 \times 10^{20}$ cm^{-2}; Stark et al. 1992). The N_H correction discussed in § 2 was applied to the SIS spectra, which for our epoch of observation was 6.8×10^{20} cm^{-2} for SIS0 and 9.8×10^{20} cm^{-2} for SIS1, with $\approx \pm 10\%$ uncertainty. The fit was not good, with $\chi^2 = 226.5$ for 137 degrees of freedom (dof). As excess absorption was indicated in the earlier spectrum of PHL 5200 (MES95) and in other BALQSOs (Mathur et al. 2000 and references therein), absorption at the source was added as a next step. The fit was better, but clearly showed negative residuals around 1 keV and positive residuals at lower energies (Figs. 1 and 2). Note that the behavior of the low-energy residuals is exactly opposite to that due to the low-energy calibration problem, which produces spurious negative residuals. The implied recovery of the underlying power law is a typical signature of partial covering by the absorber. So we fitted the spectrum with a partial covering model, and the fit was significantly better ($\chi^2 = 182.5$, 135 dof). The resulting $N_H = (5 \pm 1) \times 10^{23}$ cm^{-2}, and the covering factor is $0.9^{+0.05}_{-0.06}$. The confidence contours of the interesting parameters are plotted in Figure 3. The scale over which Figure 3 is plotted shows the range of 3 σ uncertainty in the earlier observation (MES95). The column density at the source is greater than 2×10^{23} cm^{-2}, and the power-law slope α is greater than 1.2 at 99% confidence [flux $f(E) \propto E^{-\alpha}$, where E is the energy].

The only residuals left after the partial covering model fit are those above ∼8 keV (observed frame), lying below the model values (Fig. 2). Such residuals are not expected to be a result of any calibration problems. They imply that a simple power-law continuum must turn over at higher energies. So we added a high-energy cutoff to the model and refitted the data. This resulted in a much better fit with $\chi^2_\nu = 1.18$. This "best-fit" model, however, resulted in an unusually low value of the high-energy cutoff of $E_{\rm cutoff} = 18$ keV (rest frame) with e-folding energy of 0.4 eV. The typical high-energy cutoff in quasar spectra is believed to be about 300 keV, although Yaqoob (2000) has drawn attention to the fact that this value

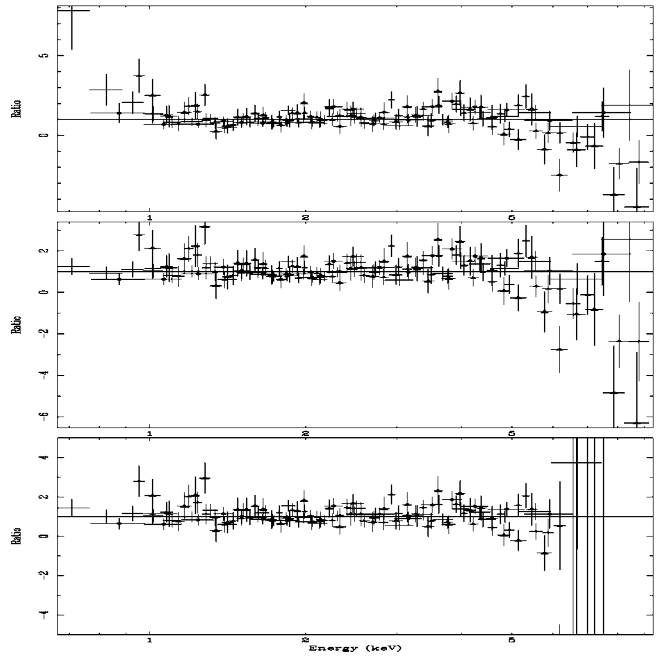

FIG. 2.—*ASCA* data of PHL 5200 divided by fitted models. *Top*: The power law, Galactic absorption, plus excess absorption at the source. Note the strong recovery at low energies. *Middle*: A partial covering model. The residuals left are at energies $\gtrsim 8$ keV. *Bottom*: Additional high-energy cutoff. *Dots*: SIS0; *circles*: SIS1; *open triangles*: GIS2; *filled triangles*: GIS3.

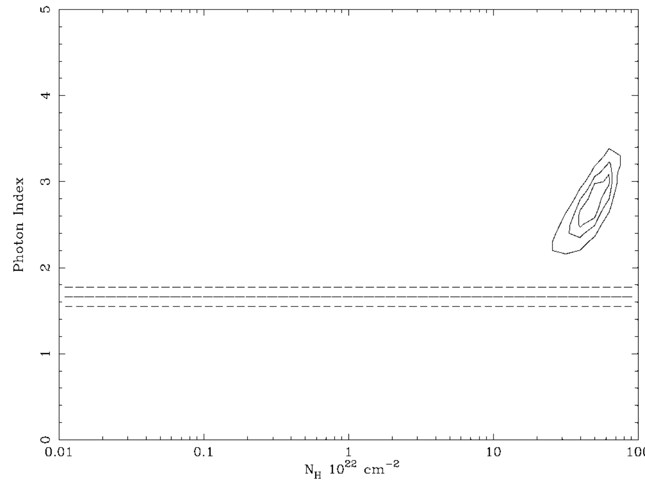

FIG. 3.—Confidence contours of the power-law photon index against the absorbing column density (the photon index is $= 1 + \alpha$). Note the large best-fit column density and the steep power-law spectrum. The horizontal lines represent the average spectral slope and range in $z \gtrsim 2$ radio-quiet quasars. The scale over which the plot is made shows 3 σ uncertainty in the previous observation.

is not well measured. We are aware of at least one another active galactic nucleus (AGN) with a very low cutoff value. In ESO 103-G35, Wilkes et al. (2001) found $E_{\rm cutoff} = 29 \pm 10$ keV. Low values of $E_{\rm cutoff}$ are likely to be important in understanding the spectrum of the cosmic X-ray background (Yaqoob 2000). We note, however, that the negative residuals observed in our spectrum of PHL 5200 are significant only in the last few channels. So we caution against attaching too much significance to this result.

As discussed above, the source is highly absorbed with $N_{\rm H} = 5 \times 10^{23}\ {\rm cm}^{-2}$. While the absorber is not Thomson thick, the effects of Thomson and Compton scattering may start becoming important at such column densities. In the analysis above, only photoelectric absorption is taken into account. The negative residuals observed at higher energies could be the effect of excess absorption due to Compton scattering, although for the observed column density it is not expected to be a significant effect (Matt, Pompilio, & La Franca 1999). Nevertheless, we refitted our spectra with a partial covering model that fully incorporates Compton scattering in the absorber, as discussed in Matt et al. (1999). The resulting parameters are $N_{\rm H} = (6 \pm 2) \times 10^{23}\ {\rm cm}^{-2}$, $\alpha = 1.9 \pm 0.4$, and covering fraction equal to 0.94 ± 0.04. These are consistent with the model without Compton scattering, as expected.

For a spherical distribution of matter with $N_{\rm H} = 5 \times 10^{23}\ {\rm cm}^{-2}$, an Fe K emission line with equivalent width (EW) of 270 eV is expected (as measured against the observed continuum). We do not detect any line at the position of Fe Kα (rest energy 6.4 keV). The upper limit on the observed EW for a narrow line is 71 eV for SIS0 data and 102 eV for GIS3 data. The corresponding rest-frame EWs are 212 and 304 eV, respectively. So we cannot put any meaningful constraint on the geometry of the absorber as viewed by the continuum source.

3. DISCUSSION

The BALQSO PHL 5200 is clearly detected in all the instruments in this deep *ASCA* observation. With a total of 2610 "good" counts, this is the best X-ray spectrum of a BALQSO yet. The parameters of the spectral fit are well constrained; the X-ray flux is highly absorbed with $N_{\rm H} = (5 \pm 1) \times 10^{23}\ {\rm cm}^{-2}$. While consistent with the conclusions of MES95, the earlier low signal-to-noise ratio spectrum was also consistent with a model with no excess absorption (see also Gallagher et al. 1999). We unambiguously confirm large absorbing column density in PHL 5200. The X-ray weakness of BALQSOs thus is surely a result of absorption.

The absorber does not cover the continuum fully, with a covering fraction 90% $\pm$ 5%. This must be the reason for the apparent lack of excess absorption and flatter spectrum in the low signal-to-noise ratio spectrum (see also Green, Aldcroft, & Mathur 2001). Partial covering of the absorber is consistent with the large optical polarization observed in this source (Goodrich & Miller 1995; Cohen et al. 1995), implying that there are at least two lines of sight to the nucleus: one direct, highly absorbed, and another scattered but unabsorbed. Gallagher et al. (1999) have discussed the possibility that partial covering by the absorber might be responsible for highly polarized BALQSOs to be relatively X-ray bright. Here we find that, indeed, that is the best-fit model to the PHL 5200 spectrum.

An associated absorber with high column density and partially covering the continuum is our preferred interpretation of the observed spectrum of PHL 5200. While physically motivated, this is not the only way to model the *ASCA* spectrum. For example, the low-energy recovery of the absorbed spectrum may be modeled as an unrelated soft excess.[6] The dip at $\approx$1 keV is also a signature of a warm absorber. Note, however, that in PHL 5200 it corresponds to a rest-frame energy of $\approx$3 keV. Since absorption due to highly ionized sulphur or silicon occurs at

[6] The nearby object, $\approx 8''$ away from the optical position of PHL 5200, is an early K star with no emission lines and is therefore very unlikely to contribute to the X-ray flux of PHL 5200.

these energies, such an interpretation might be plausible. However, it seems unlikely given that these are not among the most abundant elements.

The most surprising result of this observation is the steep spectrum, with an X-ray power-law slope $\alpha = 1.7 \pm 0.4$. This might be an additional reason behind the unexpected nondetections of BALQSOs even in sensitive hard X-ray observations (§ 1). The mean *ASCA* slope for radio-quiet quasars at high redshifts is $\alpha = 0.67 \pm 0.11$, with a dispersion of $\sigma = 0.07$ (Vignali et al. 1999; in the redshift interval between $z = 1.9$ and 2.3). Our observations imply that the spectra of BALQSOs may *not* be exactly like other radio-quiet quasars, but are steeper. The observed, absorption corrected, 2–10 keV flux is 3.7×10^{-13} ergs cm^{-2} s^{-1} (SIS0), consistent with the 1994 *ASCA* observation (MES95). So, the observed steep spectrum is unlikely to be a result of a short-lived high state. The only other BALQSO, PG 2112+059, for which a spectrum is available, has $\alpha = 0.98^{+0.4}_{-0.27}$ (Gallagher et al. 2001). As noted by Gallagher et al., this is consistent with the mean quasar slope. However, it is also consistent with a slope as steep as 1.38 at 90% confidence.

As discussed in § 2.2, CCDs on *ASCA* have been degraded over time. While we have been very careful in our analysis, there might be some unknown calibration uncertainties that have affected the results presented here. Future observations with *Chandra* and *XMM-Newton* will be useful in this respect. The discussion below assumes that these *ASCA* results are correct.

At low redshifts, Brandt, Mathur, & Elvis (1997) found that the hard X-ray spectra of Seyfert galaxies are typically flatter than about $\alpha = 1.0$. The Seyfert galaxies with steeper spectra are the narrow line Seyfert 1 (NLS1) galaxies. Brandt & Gallagher (2000) has discussed the analogy between low-ionization BALQSOs and NLS1 galaxies. Mathur (2000) has discussed the analogy between BALQSOs and NLS1 galaxies further and has argued that NLS1 galaxies may be AGNs in the making. In this scenario, young radio-quiet AGNs are accreting at a high Eddington rate and have steep spectra. Over time, the accretion rate drops and the X-ray spectrum flattens. BALQSOs may be in that early evolutionary phase when the shroud surrounding the nuclear black hole is being blown away and a quasar emerges (e.g., Fabian 1999; see also Becker et al. 2000). If the observed steep spectrum of PHL 5200 is a general property of BALQSOs, then it supports the evolutionary hypothesis of Mathur (2000) and further supports their analogy with NLS1 galaxies. On the other hand, PHL 5200 is one of the X-ray brightest BALQSOs and so may not be representative of the BALQSO population. What is more likely, however, is that its orientation and cloud geometry fortuitously allow for substantial reflection of X-rays into our line of sight.

It has been an accepted paradigm that the orientation to the line of sight determines the appearance of an AGN. In addition to orientation, the age of a quasar also seems to play a role in its appearance. The steep X-ray spectra in NLS1 galaxies are a result of their high accretion rate, close to the Eddington limit (Pounds, Done, & Osborn 1995). BALQSOs, however, are much more luminous than NLS1 galaxies and so must have far more massive black holes. Steep X-ray spectra in such systems may prove to be challenging to accretion theories.

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