X-ray Spectroscopy of QSO Absorbers

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ABSTRACT

The optical/ultraviolet (OUV) emission of QSOs has not proved a ready key to unlock the physics of the broad line region immediately surrounding the central engine of QSOs. X-ray emission suffers from a similar barrier to our understanding - many regions with widely ranging conditions may contribute, each of which may vary with a different response lag. The study of intrinsic absorption in QSOs may surmount some of these problems, if sensitive UV and X-ray data are combined.

Recent results from the *ROSAT* All Sky Survey, and from deep *ROSAT* pointings reveal that broad absorption line quasars (BALQSOs) are weak in the soft X-ray bandpass ($\alpha_{ox} > 1.8$) in comparison to QSOs with normal optical/UV spectra ($\langle\alpha_{ox}\rangle = 1.4$). The ubiquitous association of soft X-ray absorption with UV absorption suggests that the absorbers in each regime are physically associated. UV/X-ray studies show great promise for unifying many different kinds of QSOs through their often uniquely-related absorbers. We argue that since absorbed QSOs are faint in soft X-rays, a High Throughput X-ray Spectroscopy (HTXS) mission of wide bandpass and high sensitivity is critical to constraining the physics of QSO absorption line clouds, which are in turn one of the best hopes we have for probing the region immediately surrounding the AGN engine.

1. QSO Emission Lines and Outstanding Mysteries

Most of the $\sim 10,000$ QSOs to date were *discovered* either via their prominent optical and ultraviolet (OUV) emission lines, or from their distinct colors in these bandpasses. Continuum emission has also been studied in detail, but the answers to some surprisingly fundamental questions remain at large: 1) Do SEDs directly determine emission line strengths/profiles? 2) What is the balance of gravity and $p_{\rm rad}$ in broad line production? 3) What causes the Baldwin Effect (the observed nonlinear scaling of emission line with continuum flux) ? Part of the reason for the persistence of such enigmas is probably that optical/UV spectra of QSOs are remarkably similar, despite the great variety of QSO SEDs. The overall similarity of QSO emission line spectra had been taken as evidence of fairly uniform, robust physical conditions in the BELR, which encouraged the assumption that clouds in the BELR inhabit a narrow swath of parameter space (in density, size, and ionization parameter). Early photoionization pioneers such as Mushotsky & Ferland (1984) ran models on a single cloud. Refinements using cloud ensembles showed a reduced dependence of total line emission on intrinsic QSO SEDs (Binette et al. 1989). Details of individual clouds or even clouds in a single 'zone" can be lost in the mix, and correlations between continuum shape and observed line parameters diluted. Baldwin et al. (1995) reiterate that averaging of emission from clouds with a wide variety of properties (but uniformly large columns) results in QSO line spectra robustly consistent with those observed.

Are QSOs thus a P_2C_2E (process too complicated too explain; Rushdie 1990) ? Recent observational progress is beginning to approach the putative supermassive black hole in nearby AGN empirically, for example through H_2O megamasers (Greenhill et al. 1995), and gravitationally broadened/shifted Fe Kα (Fabian et al. 1995). Are OUV spectra, the first, most detailed, and most common data available for QSOs, going to prove irrelevant to our understanding of their intrinsic physics? We here offer that *absorption* intrinsic to QSOs will be a crucial key to physics in the broad line region (BLR) nearest the central engine of QSOs. The study of QSOs showng intrinsic absorption in their OUV spectra is just beginning to provide a wealth of information, particularly in conjunction with sensitive X-ray spectra.

2. UV Spectra of BALQSOs

From 10 to 15% of optically-selected QSO spectra show broad absorption line (BAL) troughs. BALs suggest a line of sight passing through highly ionized, high column density ($N_H \sim 10^{20}$ cm^{-2}) absorbers, flowing outward from the nuclear region at speeds up to 0.1 - 0.2c. Low BAL cloud covering factors and the absence of emission lines at the high velocities observed in BALQSOs, along with the similarity of emission-line and continuum properties of BAL and non-BALQSOs (Hammann, Korista, & Morris 1993, hereafter HKM; Weymann et al. 1991, hereafter WMFH) suggest that *all* radio quiet (RQ) QSOs (which in turn comprise $\sim$ 90% of all QSOs) have BAL clouds. Far from being exotic, since BAL clouds probably inhabit a region just outside the BELR ($r_{BALR} \geq r_{BELR} \sim 0.01$pc), BALQSOs offer a special probe of gas dynamics in typical QSOs.

Analysis of UV BALs yields column densities of a few ions (e.g., OVIλ1035, CIVλ1549, NVλ1240), but little information on the ionization state, and so even less on the *total* column of the absorber. Furthermore, OUV data ($N_H^{intr} \sim 10^{19}$ to 10^{20}) predict very little soft X-ray absorption ($\tau << 1$).

3. BALQSOs in SOFT X-rays

Green et al. (1995) recently demonstrated that, when compared to normal RQ QSOs, BALQSOs are weak in the soft X-ray bandpass: Their sample of 36 BALQSOs was chosen from a large uniformly-selected QSO sample (the LBQS), as observed during the *ROSAT* All-Sky Survey (RASS). Although the short (~ 600 sec) exposure times of the RASS meant that the upper limits (for 35 of the 36 QSOs) were not very sensitive, by stacking the X-ray data, they were able to show that their uniform BALQSO sample was X-ray quiet at the 99.5% significance level compared to carefully chosen comparison RQ QSO samples.

Pursuing this line of study with deep pointed observations from the *ROSAT* PSPC, Green & Mathur (1996; hereafter GM96) confirmed that BALQSOs are weak in the soft X-ray bandpass in comparison to RQ QSOs with normal OUV spectra. While a comparison sample of 10 similar RQ QSOs (from Laor et al. 1994) without BALs yielded a sample mean of $\alpha_{ox} = 1.45 \pm 0.08$, nine out of twelve reputed BAL QSOs were not detected by *ROSAT* deep pointings, yielding $\alpha_{ox} > 1.8$. Of three remaining BALs in GM96, one was too distant for an interesting lower limit to α_{ox}. One was detected, yielding $\alpha_{ox} = 1.98$, and $N_H^{intr} \sim 10^{23}\mathrm{cm}^{-2}$. Only one QSO, PG 1416–129, appeared to be X-ray bright, with a value of $\alpha_{ox} = 1.4$ typical of non-BAL QSOs. However, a new HST spectrum of this object reveals some surprises (Green et al. 1997, in preparation) which bring it into line with the hypothesis that BALQSOs are *all* weak in the soft X-ray bandpass.

If indeed the central continuum source of BALQSOs is similar to that of other QSOs, as argued above, the instrinsic absorbing columns required to explain the observed soft X-ray deficit must be at least 100 times higher than those inferred from the UV data alone ($N_H^{intr} > 2 \times 10^{22}\mathrm{cm}^{-2}$). In contrast, the non-BAL sample of PSPC observations shows no evidence at all for absorption.

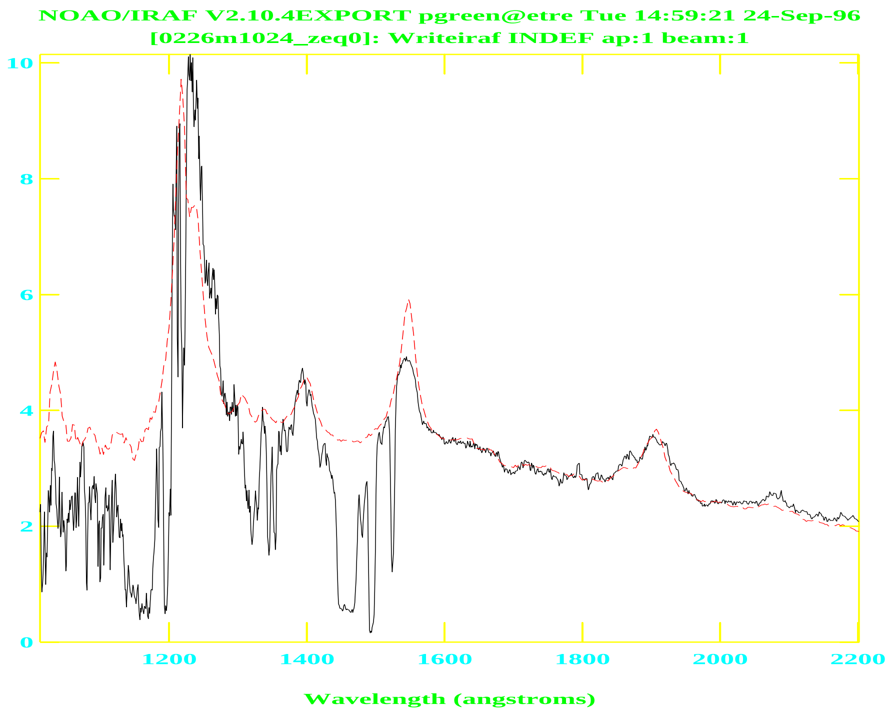

Figure 1. The rest frame spectrum of a typical BAL QSO 0226–1024 (WMFH) overlaid with a composite spectrum (Francis et al. 1991) consisting mostly of unabsorbed radio-quiet QSOs. The intrinsic continuum and the emission lines of the unabsorbed spectrum are consistent with the unabsorbed part of the BAL QSO spectrum.

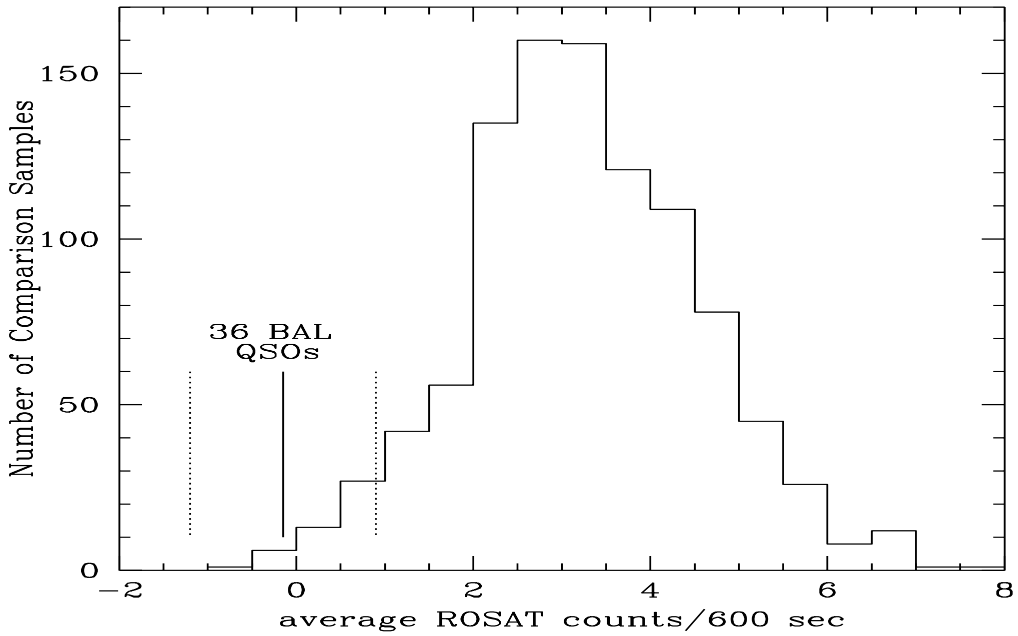

Figure 2. Histogram of countrates (per 600sec) for 1000 random subsamples of 36 QSOs from a list of 363 definite ($z > 1.3$) non-BAL QSOs, for comparison to the true BAL sample of 36 QSOs. All samples are taken from the *ROSAT* All Sky Survey (RASS) observations of Large Bright Quasar Survey (LBQS) QSOs (Green et al. 1995). The number of stacked counts for the BAL sample is indicated, with errors (square root of the area-normalized background counts) shown as dotted lines to either side. Only 5 in 1000 trials generates equal or fewer counts than the BAL sample. The sample of 36 stacked BAL QSOs thus appears to be X-ray quiet at the 99.5% level.

4. Soft X-ray Absorption and Spectral Energy Distributions

For comparison of an observed soft X-ray count rate (or its upper limit) to that expected from a typical RQ QSO, GM96 first derived an optical luminosity derived from the observed magnitude. From the optical luminosity, an intrinsic soft X-ray flux is then predicted using the mean slope α_{ox} of a hypothetical power law connecting rest-frame 2500 Å and 2 keV as derived for non-BAL RQ QSOs in the *ROSAT* PSPC (Green et al. 1995). The expected PSPC count rate corresponding to this flux is derived assuming a power-law model with $\alpha_E = 1.5$ (the mean PSPC α_E for radio-quiet quasars; Laor et al. 1994) and the Galactic column density. If the expected PSPC count rate from PIMMS was greater than observed (as is the case for all BALQSOs), the column density of the absorber in the spectral model was increased until the observed count rate/upper limit was reached. This resulted in a *lower* limit to the 'observed' intrinsic column N_H^{intr}, on the assumption that the absorber is cold gas with solar metallicity $Z = Z_\odot$. Many of these assumptions could be bypassed, greatly increasing the reliability of the conclusions, if high signal-to-noise ratio (SNR), wide bandpass X-ray spectroscopy could be obtained. The implications of currently required assumptions are briefly outlined below:

Although $Z = Z_\odot$ is assumed, line ratios in high-z (non-BAL) QSOs suggest $2 < Z/Z_\odot < 10$ (Hamann & Ferland 1993), and estimates of N_H^{intr} are inversely proportional to the assumed metallicity. However, unless AGN have abundances 100 times solar (Turnshek 1988), column densities at least an order of magnitude higher for BALQSOs than is typical for RQ QSOs are still required.

If instead of neutral gas, $U \sim 0.1$ is assumed (based on photoionization models of the OUV data; HKM), then our N_H^{intr} estimates would *rise* by about an order of magnitude. Even higher ionization ($U \geq 1$) are likely to be required.

Perhaps the most critical assumption is that BALQSOs harbor the same intrinsic (unabsorbed) spectral energy distribution (SED) as normal RQ QSOs. So far, PHL 5200 provides the only direct evidence for this. An *ASCA* spectrum of PHL5200 shows a best-fit spectral slope $\alpha_E = 0.6^{+0.9}_{-0.6}$ is normal for an RQ QSO. The resulting $\alpha_{ox} = 1.5$, is also normal for an RQ QSO. Excess absorption is required at 99% confidence: $N_H^{intr} = 0.2 - 4 \times 10^{23}\ \frac{Z_\odot}{Z}$ cm^{-2} at the source (Mathur, Elvis, & Singh 1996). This indeed confirms that, although BALQSOs are X-ray quiet, it is strong absorption in the BAL region that makes them appear faint to low energy X-ray experiments. Since the required intrinsic absorbing column density is two to three orders of magnitude larger than that derived from UV estimates of column densities in BALQSOs, BAL systems are much more highly ionized than previously thought. Unfortunately, PHL 5200 is one of less than a handful of QSOs bright enough for this sort of analysis with ASCA.

Since BALs span a wide range in velocity, most models of BAL cloud outflows require either an ensemble of clouds along the line of sight, or winds blown off the surface of the accretion disk (deKool & Begelman 1995; Murray & Chiang 1995). Most BALQSO models reproduce columns as inferred from OUV data alone ($N \sim 10^{20}$cm^{-2}). However, entrained disk wind models produce column densities of $10^{23} - 10^{24}$ cm^{-2}, consistent with the N$_H^{intr}$ so far derived from *ROSAT* PSPC observations.

If the BALQSO phenomenon is indeed only a viewing angle effect, then hard X-ray emission (>10 keV) should show fluxes and slopes typical for normal RQ QSOs. The results for PHL 5200 look promising, and we have been awarded XTE time to further pursue hard X-ray studies of BALQSOs LBQS 2212-1759 and PG1700+518.

5. Are the UV And X-Ray Absorbers The Same Material?

Intrinsic “associated” absorption has been a well known but little understood phenomenon in ultraviolet studies of both low and high luminosity active galactic nuclei (AGN) and in X-ray observations of the former. The possibility that both UV and X-ray absorption is produced by the same gas is an attractive one, but attempts to reconcile the two had until recently been unsuccessful (e.g. Kolman *et al* 1993).

ROSAT observations of the quasar 3C351 (z=0.371) have revealed the presence of a ‘warm absorber’ in its X-ray spectrum showing a K-edge due to OVII or OVIII (Fiore *et al* 1993). 3C351 also shows unusually strong, associated, high ionization absorption lines in the HST ultraviolet spectrum (Bahcall *et al* 1993) including OVI $\lambda\lambda 1031, 1037$. Through detailed photoionization modeling, Mathur (1994) and Mathur et al. (1995) found an excellent match between the X-ray and UV absorber properties. The combination of both datasets allows strong constraints to be placed upon the physical conditions of the absorber. In 3C351, the absorber appears to be well-described by material quite similar to that seen in BALQSOs; highly ionized, outflowing, low density material situated outside the broad emission line region (BELR).

Since the discovery of a joint X-ray/UV absorber in an ‘X-ray quiet’ quasar 3C351, consistent properties of UV and X-ray absorbers have been noted in a ‘red’ quasar 3C212 (Mathur 1994), and in the variable Seyfert galaxy NGC5548 (Mathur *et al* 1995). This opens up the possibility that the wide range of associated absorbers could form a continuum of properties deep in the active nucleus.

6. BAL Variability

Absorption line variability has been measured both in narrow associated absorbers, and in BALs (Koratkar et al. 1996; Barlow et al. 1992). About 15% of BALs show variability in the residual absorption intensity (normalized flux within the line), at the level of $\leq 20\%$ (Barlow 1994; Smith & Penston 1988). The resulting change in column is measured to be $\Delta N > 10^{14}\mathrm{cm}^{-2}$. Is there a concomitant change in absorption in the soft X-ray regime?

A demonstration of correlated variability between BALs and soft X-ray flux in true BALQSOs would provide strong evidence that the UV and soft X-ray absorbers are indeed physically associated. Since BALs show *long stable states* between variability, an event found in a campaign of ground-based optical monitoring could provide a target of opportunity for followup X-ray spectroscopy. Unfortunately, such studies present a daunting task for the current generation of X-ray telescopes, given the weak soft X-ray fluxes of BALQSOs. However, with the larger effective areas proposed for high throughput X-ray spectroscopy missions, UV/X-ray variability studies could not only confirm the physical identity of UV/X-ray absorbers, but also determine whether BAL variability is a result of a true change in column (e.g., due to motion of the absorber out of the line of sight), or in ionization. A variable photoionizing continuum might cause a change in the ionization levels, and thus a redistribution of the fractional abundances of the ions, resulting in the strengthening or weakening of the absorption lines.

Limits on n_e and the response time scale of the BAL changes indicate that $0.1 \leq r_{BAL} \leq$100pc from the ionizing source, so that the inner regions nearest the massive black hole can be studied using BALs. The great advantage of studying absorption rather than emission variability is that, unlike in the BELR, the BAL variation mechanism travels in step with the continuum emission, rendering unnecessary the prohibitively complicated (and observationally expensive) deconvolution of a temporal response function.

7. The Potential of HTXS as a PROBE of the BALR

Some very achievable goals for HTXS study of absorbed QSOs are outlined above: 1) Verify that intrinsic SEDs are consistent for BAL and RQ QSOs. 2) Constrain the column density (N_H), ionization parameter (U) and the ion abundances of the absorbing clouds. 3) Describe the location and dynamics of the absorbing gas.

One of the fundamental such questions still eluding an answer is why BALs are found only among radio-quiet QSOs. Only in the hard X-ray regime do BAL, non-BAL, RQ and RL QSOs all boast spectra that are both bright *and* distinct. High throughput spectroscopy in this bandpass would go a long way toward establishing a connection among the different kinds of QSOs and related absorbers: BALQSOs $\rightarrow$ high ionization associated absorbers $\rightarrow$ high + low ionization absorbers $\rightarrow$ MgII absorbers $\rightarrow$ red quasars. Thus HTXS offers promise for the still-elusive unification of diverse types of AGN. An observational mapping of the apparent diversity of AGN represents a deprojection onto a more physical basis set that must consist of at least such fundamental physical properties as 1) black hole mass and accretion rate, 2) orientation of accretion disk and jet normal to the line of sight and the plane of the host galaxy 3) abundances, densities, and ionization of intervening absorbers.

8. CONCLUSION

A marked soft X-ray deficit is a defining characteristic of BALQSOs, caused by absorption by high column density, ionized material along the line of sight. Such absorption, especially in tandem with UV absorption, can be used to nail down the intrinsic column *and* the ionization state of clouds deep inside the QSO nucleus. These in turn will greatly illuminate continuing debate surrounding such questions as the intrinsic SEDs of QSOs, the balance of gravity and $p_{\rm rad}$ in the broad line region, production, and the effect of changes in luminosity and ionization on clouds. A HTXS mission of wide bandpass and high sensitivity is critical to constraining the physics of QSO Broad Absorption Line clouds, which are in turn one of the best hopes we have for understanding the region immediately surrounding the AGN engine.

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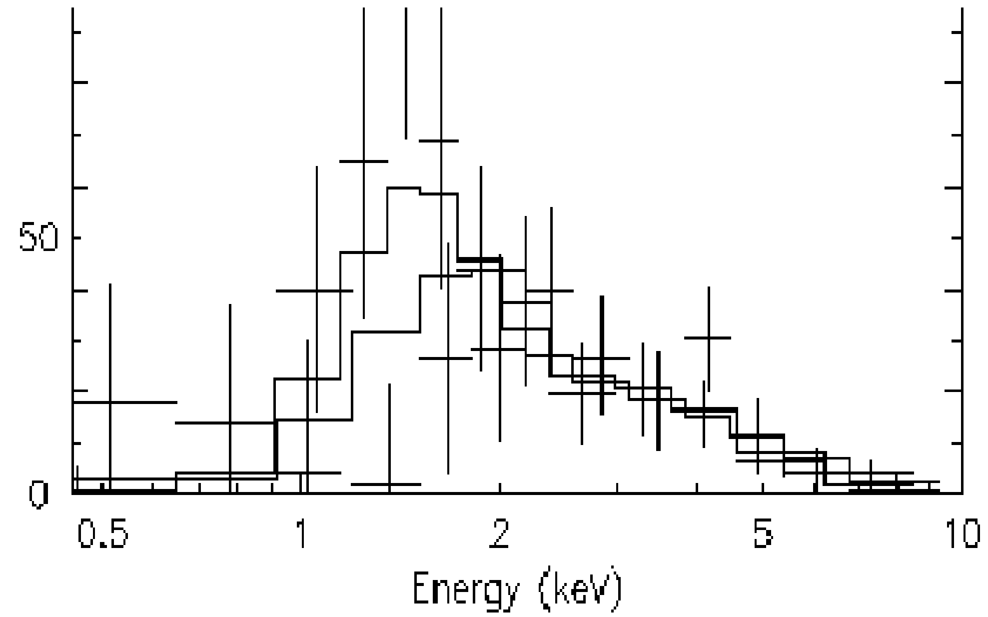

Figure 3. ASCA X-ray spectra of PHL 5200 from Mathur, Elvis & Singh 1996. This shows the ASCA SIS and GIS spectra (upper and lower data points, respectively) of the BAL QSO PHL 5200. The ordinate is in counts/keV. The best fit model shown as histograms consists of an absorbed power law of slope $\alpha_E = 0.6$. Although this slope is normal for a RQ QSO, excess absorption is required at 99% confidence: $N_H^{intr} = 0.2 - 4 \times 10^{23} \frac{Z_\odot}{Z}$ cm^{-2} at the source. This confirms that, although BALQSOs are X-ray quiet, it is strong absorption in the BAL region that makes them appear faint to low energy X-ray experiments.

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