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An Exploratory *Chandra* survey of Large Bright Quasar Survey broad absorption line QSOs

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Abstract. We are in the process of obtaining a complete sample of exploratory X-ray observations of broad absorption line (BAL) QSOs from the Large Bright Quasar Survey (LBQS). This survey is composed of short (5–7 ks) *Chandra* ACIS-S3 observations designed to significantly constrain X-ray fluxes and hardness ratios. Our sample avoids the selection biases of some previous surveys while providing X-ray data of similar quality. Of 17 BAL QSOs observed to date, 13 are detected. In general, our results are consistent with absorption as the primary cause of X-ray weakness in BAL QSOs. As found by Green et al. (2001), those BAL QSOs with low-ionization absorption lines are found to be notably X-ray weaker than BAL QSOs with only high ionization lines.

1. Introduction

From studies with *ROSAT* and *ASCA*, Broad Absorption Line (BAL) QSOs are known to have faint soft X-ray fluxes compared to their optical fluxes (e.g., Green et al. 1995; Green & Mathur 1996; Gallagher et al. 1999) Given the extreme absorption evident in the UV, this soft X-ray faintness was assumed to result from intrinsic absorption. At the time, the X-ray data could not explicitly demonstrate this, though the strong correlation found by Brandt, Laor, & Wills (2000; hereafter BLW) between C IV absorption equivalent width (EW) and faintness in soft X-rays supported this assumption. The observation of PG 2112+059 with *ASCA* provided the first solid spectral evidence for intrinsic X-ray absorption and a normal underlying X-ray continuum in a BAL QSO (Gallagher et al. 2001). Subsequently, more observations of BAL QSOs with *Chandra* also found signatures of intrinsic X-ray absorption (e.g., Green et al. 2001).

Gallagher et al. (2002) compiled the results from the first moderate-sized survey of BAL QSOs with enough counts for X-ray spectroscopic analysis. They concluded from the spectroscopic evidence that the intrinsic UV-to-X-ray spectral energy distributions of BAL QSOs are consistent with those of typical QSOs. Furthermore, complex, intrinsic absorption with $N_{\rm H} = (0.1\text{–}4) \times 10^{23}$ cm^{-2} is generally evident in the X-ray spectra. At present, however, only a handful of these generally faint targets have provided data of sufficient quality for spectral analysis. This sample is generally diverse, and thus far there is no known predictor of observed 0.5–10.0 keV flux based on the spectral properties in other wavelength regimes. In other words, there has been no obvious connection between the characteristics of the UV and X-ray absorbers as of yet, though all QSO with broad UV absorption also apparently have X-ray absorption.

In an effort to remedy this situation, we are in the process of compiling the multi-wavelength properties of a complete sample of BAL QSOs from the Large Bright Quasar Survey (LBQS; Hewett, Foltz, & Chaffee 1995). The sample will ultimately include all 37 of the BAL QSOs from the LBQS with $z > 1.35$, the redshift at which the definitive C IV BAL is shifted into the wavelength regime accessible to ground-based spectroscopy. The optically bright targets are drawn from a homogeneous, magnitude-limited survey that has effective, well-defined and objectively applied selection criteria (e.g., Hewett, Foltz, & Chaffee 2001). One of the ultimate goals of this survey is to understand the connection between UV and X-ray absorption in luminous QSOs, and hence gain some insight into the mechanism for launching and maintaining energetic winds. To further this project, we are in the process of observing each object in X-rays and in the rest-frame UV. In this paper, we present preliminary results from the analysis of the exploratory *Chandra* Advanced CCD Imaging Spectrometer (ACIS; G. P. Garmire et al., in preparation) observations of the first 17 targets which have been observed to date. These short (5–7 ks) observations are intended to determine the basic X-ray fluxes and rough spectral shapes of the sample, and for those targets that were not detected, sensitive upper limits can be set with these exposure times. In addition to presenting new X-ray results, we also compare these data to some of the multiwavelength information available in the literature. All of the QSOs in this sample were observed in the spectroscopic BAL QSO survey of Weymann et al. (1991, hereafter WMFH), and so a significant amount of data is available both from this work and others based on the WMFH sample.

2. Observations and X-ray Data Analysis

Each target was observed at the aimpoint of the back-illuminated S3 CCD of ACIS in faint mode. The data were processed using the standard *Chandra* X-ray Center (CXC) aspect solution and grade filtering. Of the 17 observed BAL QSOs, 13 were detected with counts ranging from 4–84 photons. After determining the position of the X-ray centroid, the counts in the full (0.35–8.0 keV), soft (0.35–2.0 keV), and hard (2.0–8.0 keV) bands were extracted from a source cell with a radius of 2″.5. The hardness ratio (HR), defined as the number of 2.0–8.0 keV counts divided by the number of 0.35–2.0 keV counts, was then calculated; this parameter provides a coarse quantitative measure of the spectral shape. In order to transform the HR into a physical parameter, the photon index, for characterizing the X-ray spectrum, observations of power-law X-ray spectra were simulated using the X-ray spectral modeling tool, XSPEC (Arnaud 1996). For reference, a typical QSO with no intrinsic absorption and a photon index, $\Gamma = 2.0$, would have been observed to have HR=0.13–0.15 for the range of Galactic column densities of $(1.6–4.8)\times10^{20}$ cm^{-2} in this sample. Once the value of Γ corresponding to the observed HR and Galactic $N_{\rm H}$ was determined, the model power-law spectrum was normalized using the full-band count rate. Given a photon index and normalization, the derived X-ray properties, $F_{\rm X}$ (observed-frame 2–8 keV flux) and $f_{2\ {\rm keV}}$ (flux density at rest-frame 2 keV) could be calculated. Finally, $\alpha_{\rm ox}$, the slope of a hypothetical power law connecting f_{2500}, the flux density at 2500 Å, with $f_{2\ {\rm keV}}$, was determined.

3. Testing for Significant Correlations

Utilizing the available UV and optical data in the literature, we sought evidence for correlations that might indicate a connection between the X-ray properties and those in other parts of the spectrum. To start, we considered the "BALnicity index" (BI), a conservative measure of the C IV absorption equivalent width originally defined and tabulated by WMFH. If the extent of X-ray weakness is due to intrinsic absorption, $\alpha_{\rm ox}$ might be expected to correlate with the BI. To test for such a relationship, we calculated the non-parametric Kendall's τ statistic.

As can be seen in Figure 1, there is no evident correlation between the C IV absorption-line BI and $\alpha_{\rm ox}$; this is supported by the high probability, $P = 0.28$, that the null hypothesis is consistent with these data. This result could be considered surprising given that Brandt et al. (2000) found a highly statistically significant correlation between C IV absorption EW and $\alpha_{\rm ox}$. However, their sample, the Bright Quasar Survey (Schmidt & Green 1983) objects

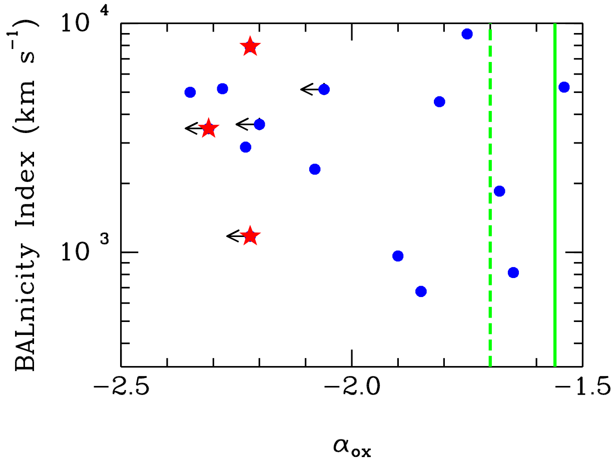

Fig. 1. BALnicity index vs. $\alpha_{\rm ox}$. The BI values are from WMFH; this absorption-line parameter does not have a statistically significant correlation with weakness in X-rays. The solid and dashed vertical lines represent the mean and one standard deviation of $\alpha_{\rm ox}$ for typical radio-quiet QSOs from Brandt et al. (2001). The stars in this and subsequent plots indicate low-ionization BAL QSOs.

with $z < 0.5$, encompassed a much larger dynamic range of both $\alpha_{\rm ox}$ and absorption EW; the majority of their sample exhibited neither weakness in X-rays nor C IV absorption. Our BAL QSO sample is probing the most extreme end of C IV absorption, where the straightforward relationship between weakness in soft X-rays and UV continuum absorption apparently does not hold. Given the well-documented complexity of BAL profiles, which can include contributions from scattered flux as well as exhibit severe saturation (e.g., Ogle et al. 1999; Arav et al. 2001), the observed lack of correlation is perhaps not remarkable.

We also investigated possible correlations between the UV continuum shape and X-ray properties. Though the slope of the continuum blueward of C III], α_B, is not correlated significantly with $\alpha_{\rm ox}$, there are some interesting trends in the data (see Figure 2). First, all of the BAL QSOs with the reddest continua (largest values of α_B) reside at the X-ray weak end of the sample. However, not all of the X-ray weakest BAL QSOs are red. If $\alpha_{\rm ox}$ can be associated with the amount of intrinsic X-ray absorption, this suggests that the X-ray absorbing gas does not necessarily cause continuum reddening. Physically this could result from absorbing gas with very low gas-to-dust ratio as has been seen in Seyfert galaxies (Maiolino et al. 2001, and references therein). Furthermore, dusty absorbers responsible for continuum reddening may not be identical to those causing X-ray weakness.

The search for correlations between absorption-line and continuum properties with $\alpha_{\rm ox}$ did not result in any obvious patterns, but those with the HR proved more fruitful. Though individual measurements of the HR suffer from large statistical errors, the ensemble of HRs from the sample offers promise for investigating the relationship of observed X-ray continuum shape to other properties. Tests

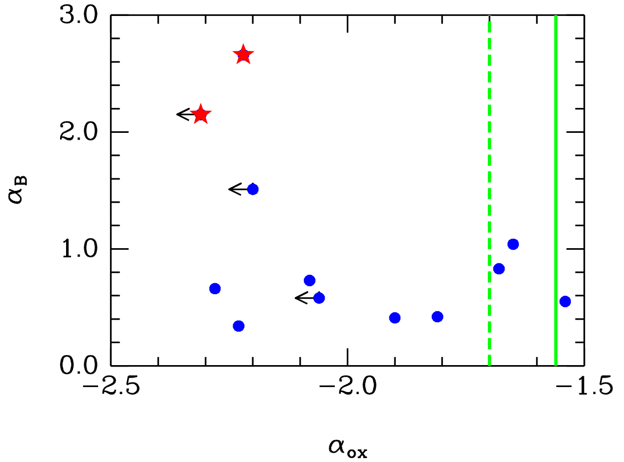

Fig. 2. The spectral index of the continuum blueward of C III], α_B for $F_\nu \propto \nu^{-\alpha_B}$, versus $\alpha_{\rm ox}$. Note that the reddest BAL QSOs (those with the largest values of α_B) are also X-ray weak. The values for α_B are from Hutsemékers et al. (1998). The vertical lines in the plot are as defined for Figure 1.

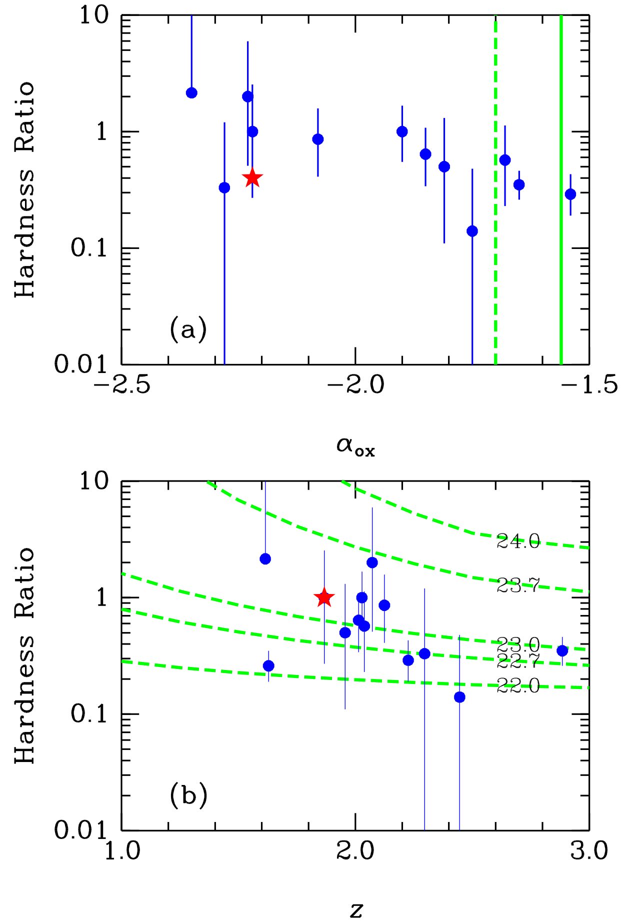

Fig. 3. **(a)** Hardness ratio versus $\alpha_{\rm ox}$. The weakest X-ray sources (relative to their UV continuum flux) tend to have the hardest spectra. The star symbols and vertical gray lines are as defined in the caption to Figure 1. **(b)** Hardness ratio versus z. The dashed curves represent the expected HR for a power-law continuum with $\Gamma = 2.0$, Galactic $N_{\rm H}= 2.8 \times 10^{20}$ cm^{-2} (the median value for this sample), and an intrinsic, neutral column density with the log value labeled in the figure. These curves are meant for reference only as the actual absorption is likely to be complex (Gallagher et al. 2002).

of HR versus $\alpha_{\rm ox}$ resulted in a statistically significant correlation (see Figure 3a). According to the evaluation of Kendall's τ, this correlation is significant at the $\gtrsim 99\%$ confidence level. While typical QSOs have rest-frame 2–10 keV photon indices of $\Gamma = 1.9 \pm 0.27$ (e.g., Reeves & Turner 2000), a QSO exhibiting intrinsic absorption will have an apparently harder X-ray spectrum due to the lack of low-energy X-rays. Thus, a larger value of the HR might result from intrinsic absorption, which would also cause more negative values of $\alpha_{\rm ox}$.

With these data, there is no statistically significant evidence for a correlation between HR and z. At higher z, the spectral signatures of intrinsic absorption are pushed to lower observed energies, and therefore occupy less of the soft X-ray bandpass. An increase in HR with decreasing z would therefore be expected if all BAL QSOs had similar amounts of intrinsic absorption.

4. Discussion

The sample of BAL QSOs presented in this paper offers the advantage of being much more homogeneous than those in previous hard-band surveys (e.g., Gallagher et al. 1999; Green et al. 2001). With the aim of obtaining the best X-ray constraints, these samples included the optically brightest BAL QSOs known, which were drawn from surveys employing diverse selection criteria. As a result, these objects were not necessarily representative of the global properties of the BAL QSO population as a whole. In contrast, all of our targets are drawn from the same well-defined survey. In addition, our survey objects have uniform, high-quality spectroscopic data from the rest-frame UV available for meaningful comparisons between properties in different wavelength regimes.

From the days of *ROSAT* and *ASCA*, the detection fraction of BAL QSOs has increased substantially. Of the 17 observed LBQS BAL QSOs, 13 were detected. Given the sensitivity of *Chandra*, meaningful upper limits on X-ray flux and $\alpha_{\rm ox}$ could be set for those that were not detected. For the observed values of $\alpha_{\rm ox}$, our range encompasses values from -2.35 to -1.29 with four upper limits and a median value of -2.06. For comparison, the mean and standard deviation for QSOs without evident UV absorption is -1.56 ± 0.14 (Brandt et al. 2001). Not all of the BAL QSOs are observed to have $\alpha_{\rm ox}$ values that would group them as X-ray weak, e.g., with $\alpha_{\rm ox} < -1.7$. While the calculated X-ray fluxes do suffer from large errors due to the generally low count rates, $\alpha_{\rm ox}$ is not extremely sensitive to these errors. Another possible source of the spread is variability of the UV continuum since some of these fluxes were last measured more than 20 years ago (Hewett et al. 1995). However, $\alpha_{\rm ox}$ is a robust parameter; for reference, an increase in f_{2500} of a factor of 2 would result in $\Delta\alpha_{\rm ox}\approx 0.1$.

From the X-ray data alone, we have evidence consistent with the interpretation of intrinsic absorption as the cause of X-ray weakness: the significant correlation of HR and $\alpha_{\rm ox}$. An X-ray spectrum exhibiting intrinsic absorption by neutral, partial-covering, or ionized gas will have fewer counts in the soft band, and thus a higher value for the hardness ratio. At larger redshifts, the absorbed part of the spectrum will be shifted to lower and lower energies thus occupying a smaller fraction of the observed bandpass. Therefore, for a given column density, an absorbed QSO at a lower redshift will have a higher value of HR than the same QSO at a higher z. This pattern is illustrated with the dashed lines in Figure 3b. However, making a straight identification of $\alpha_{\rm ox}$ with column density is problematic for two significant reasons. First, Gallagher et al. (2002) have shown that the intrinsic absorption is complex, but with the present spectral resolution and signal-to-noise ratio, the specific nature of that complexity is poorly constrained. Thus the assumption of neutral absorption, while useful for reference, is probably not valid. The effect of ionization state, covering fraction, and velocity structure on measured column density from a CCD spectrum remains to be quantified. Empirically, this complexity manifests itself as additional flux at soft energies over what would be expected from a completely neutral absorber. Given that situation, the HR and $\alpha_{\rm ox}$ data presented in this sample should not be translated into measurements of intrinsic column density.

As found by Green et al. (2001), the low-ionization BAL QSOs in this sample (indicated by stars in Figures 1–3) also inhabit the X-ray weak end of $\alpha_{\rm ox}$. Attempting to correct the UV continua for dust extinction in these red QSOs would only push $\alpha_{\rm ox}$ to more negative values. Given this evident distinction in the X-ray as well as the UV properties, it is important to distinguish the samples of low and high-ionization BAL QSOs when trying to generalize about the population of BAL QSOs as a whole.

5. Future Work

Many BAL QSO studies have observed the most notable of objects. While they frequently offer interesting case studies, this situation can lead to spurious connections and inhibit understanding of populations as a whole. To avoid this pitfall, we are collecting exploratory X-ray observations of a complete sample of BAL QSOs in conjunction with spectroscopic X-ray data of the brightest ones. By the end of 2002, we will have 5 additional exploratory observations. Furthermore, we are in the process of obtaining rest-frame UV photometry and spectroscopy for a complete sample of LBQS BAL QSOs, as described in §1, to supplement the information in the literature as well as the *Chandra* data. The imaging and spectroscopy, obtained with the Hobby-Eberly Telescope within one month of each *Chandra* observation, will enable concurrent determinations of both f_{2500} and $f_{2\ \rm keV}$ for measuring $\alpha_{\rm ox}$, as well as the absorption-line parameters. Finally, these data will provide the means to investigate long-term variability of the velocity structure of the BALs to test the radiation-driven wind models of Proga, Stone, & Kallman (2000). In their hydrodynamical models, they predict variability on timescales of a few years. The most comprehensive BAL QSO variability study to date, that of Barlow (1993), was not of sufficient duration to test these models. With the data of WMFH and our Hobby-Eberly Telescope spectroscopy, we can approximately triple the timescale of Barlow (1993) to span more than a decade.

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