Probing Broad Absorption Line Quasar Outflows: X-ray Insights

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ABSTRACT

Energetic outflows appear to occur in conjunction with active mass accretion onto supermassive black holes. These outflows are most readily observed in the ~ 10% of quasars with broad absorption lines, where the observer’s line of sight passes through the wind. Until fairly recently, the paucity of X-ray data from these objects was notable, but now sensitive hard-band missions such as Chandra and XMM-Newton are routinely detecting broad absorption line quasars. The X-ray regime offers qualitatively new information for the understanding of these objects, and these new results must be taken into account in theoretical modeling of quasar winds.

INTRODUCTION

Recent studies of the strong correlations between black hole masses and the properties of their hosts’ galactic bulges (e.g., Ferrarese and Merritt, 2000; Gebhardt et al., 2000) demonstrate clearly the intimate interrelation between the growth of black holes and their host galaxies. This connection implies a physical mechanism for regulating the coeval development of these structures. During the bulk of their accretion phases, supermassive black holes apparently reveal themselves as luminous quasars (e.g., Yu and Tremaine, 2002), and thus quasar winds are likely to provide a primary source of feedback. These winds are directly observed in the population of Broad Absorption Line (BAL) quasars, ~ 10% of the quasar population that exhibit deep, broad absorption lines from high-ionization UV resonance transitions. Such blueshifted absorption features are understood to arise along lines of sight which pass through radiatively driven winds with terminal velocities reaching 0.1–0.3c. These energetic outflows are important components of quasar environments; mass ejection is apparently fundamentally linked to active mass accretion. X-rays, generated in the innermost region surrounding accreting black holes, travel through the nuclear environments to the observer. X-ray studies of BAL quasars thus offer a privileged view through the wind.

The challenge of accelerating gas to the high velocities observed in BAL quasars led Murray et al. (1995) to a picture similar to that presented in Figure 1. In this model, at radii starting at ~ 10^{16} cm for a 10^8 M_\odot black hole, radiation and gas pressure lift material from the disk photosphere where it is struck by light from the inner accretion disk and corona. The wind, initially co-rotating with the disk, is accelerated radially by the momentum of UV line photons; the material launched from the innermost radii reaches the highest terminal velocities. In order to prevent the wind from becoming completely ionized by soft X-rays, a second layer of shielding gas with N_H = 10^{22}-10^{24} cm^{-2}, was introduced to protect the wind from becoming completely ionized by soft X-rays. In the subsequent hydrodynamical modeling of line-driven quasar winds by Proga, Stone, and Kallman (2000), this layer of shielding gas arose naturally from the simulations. This scenario produces several predictions for X-ray observations of BAL quasars:
thus preventing it from being radiatively driven by UV line pressure. From soft X-ray and extreme UV radiation. These photons would otherwise strip the gas in the wind of electrons, thus preventing it from being radiatively driven by UV line pressure.

The patterned gray circle represents the X-ray emitting region surrounding the black hole. The region of highly ionized plasma marked “Shielding Gas” was postulated to shield the BAL wind (with a scale of light days) from soft X-ray and extreme UV radiation. These photons would otherwise strip the gas in the wind of electrons, thus preventing it from being radiatively driven by UV line pressure.

- BAL quasars should have intrinsic X-ray continuum shapes (with $\Gamma = 2.0 \pm 0.3$; e.g., George et al., 2000) and spectral energy distributions typical of radio-quiet quasars.
- All BAL quasars should be X-ray weak, i.e., have values of $\alpha_{\text{ox}} \leq -2.0$ as a result of large column densities of absorbing gas. Furthermore, with data of sufficient quality, the spectra will show the signatures of absorption by highly ionized gas.
- A correlation between the minimum absorption velocity and $\alpha_{\text{ox}}$ is likely to arise due to effects of orientation. For example, a line of sight close to the accretion disk will pass through more X-ray absorbing gas, and the minimum observed UV absorption velocity will be close to zero as the gas outflow is primarily transverse to the line of sight.

The sample of BAL quasars observed by Chandra and XMM-Newton is steadily growing, and the current X-ray data are now of sufficient quality to investigate these predictions directly. In this paper, we summarize the insights offered from both exploratory and spectroscopic X-ray surveys of BAL quasars to the understanding of quasar winds.

### RESULTS FROM EXPLORATORY SURVEYS

Given the extreme faintness of BAL quasars in the soft X-ray regime (e.g., Kopko et al., 1994; Green and Mathur, 1996), obtaining detailed spectroscopic information requires a significant commitment of observatory time. In this situation, only a small fraction of the population will have data of spectroscopic quality, and there is a legitimate danger that the conclusions drawn from such limited, potentially biased samples will not be representative of the population as a whole. Pursuing an alternate strategy of exploratory observations enables much larger numbers of BAL quasars to be observed with the goal of measuring X-ray flux, hardness ratio, and $\alpha_{\text{ox}}$ for each object. The low background and excellent spatial resolution of Chandra allow short, exploratory observations of 5–7 ks to reach sensitive flux limits of $\lesssim 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ in the 0.5–8.0 keV band (George et al., 2001; Gallagher et al., 2002a).

We are in the process of compiling the largest exploratory survey to date, with a well-defined sample of BAL quasars drawn from the Large Bright Quasar Survey (LBQS; Pultz et al., 1988; Hewett et al., 1997). This sample of $z > 1.35$ BAL quasars is comprised of 22 objects with publicly available rest-frame UV spectroscopy from Weymann et al. (1991). To date, 15 of the 20 objects observed have been detected, and the remainder have tight upper limits on both X-ray flux and $\alpha_{\text{ox}}$ (Gallagher et al., 2002a, in prep.).

Though the BAL quasars in our sample are indeed weak in X-rays with a median value of $\alpha_{\text{ox}} = -2.2$ (see Figure 2), they are generally detectable with the current generation of X-ray observatories. For those

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1 The quantity $\alpha_{\text{ox}}$ measures the relative flux densities at rest-frame 2 keV and 2500 Å. For reference, a sample of low-redshift radio-quiet quasars without known absorption has $\alpha_{\text{ox}} = -1.56 \pm 0.14$ (Brandt et al., 2001); more negative values of $\alpha_{\text{ox}}$ indicate a quasar is X-ray weak relative to its UV power.

2 At $z > 1.35$ blueshifted C IV absorption, the definitive BAL quasar signature, enters the observed LBQS wavelength range.
Fig. 2. Histogram of the $\alpha_{\text{ox}}$ values from the LBQS BAL quasar exploratory survey. The solid line is the entire sample, while the dotted line is the sample of LoBAL quasars. The arrows indicate upper limits. For comparison, the dashed gray line represents the low-redshift Palomar-Green sample of unabsorbed radio-quiet quasars from Brandt et al. (2000).

objects that are detected, a measurement of the hardness ratio indicates what fraction of the full-band (0.5–8.0 keV) counts are coming from hard band (2–8 keV) X-rays. Absorbed quasar spectra will have larger values of the hardness ratio as the cross-section for photoelectric absorption in the X-ray band decreases rapidly with increasing energy. The trend of increasing hardness ratio with decreasing $\alpha_{\text{ox}}$ illustrated in Figure 3 is therefore consistent with the understanding that X-ray faintness arises from intrinsic absorption. While this result is not new, it supports the idea that $\alpha_{\text{ox}}$ can be used in a rough sense to indicate the extent of absorption. Following this premise, $\alpha_{\text{ox}}$ might be expected to correlate with UV absorption properties such as C IV absorption-line equivalent width, as demonstrated by Brandt et al. (2000) for their sample of Palomar-Green quasars. To complement Brandt et al. (2000) we are probing the extreme end of this parameter space with the BAL quasars. In this regime, there are no apparent correlations between $\alpha_{\text{ox}}$ and several absorption-line properties for the BAL quasars, most significantly the minimum velocity of C IV absorption shown in Figure 3.

Furthermore, the large column densities of absorbing gas implied by values of $\alpha_{\text{ox}} \lesssim -2.0$ coupled with the blue UV continua of the majority of our sample imply that the X-ray absorbing gas contains little dust, at least as we know it. This is consistent with the X-ray absorber being located within the dust sublimation radius. Alternatively, the bulk of the X-ray absorption may lie interior to the UV emission region, though this implies even smaller radii for the absorption.

We also confirm the result of Green et al. (2001) that the BAL quasars with broad Mg II absorption, the LoBAL quasars, are notably X-ray weaker than those with only high-ionization BALs. In fact, only one of the LoBAL quasars in our sample was actually detected (see Figure 2). Given that LoBAL quasars generally have reddened optical and UV continua, it is unclear whether the extreme X-ray absorption that they suffer is occurring on the small scales inferred for the high-ionization BAL quasars. However, X-ray variability of the LoBAL quasar Mrk 231 suggests that a substantial X-ray absorber is located within $\sim 10^{15}$ cm of the X-ray continuum source (Gallagher et al., 2002c).

RESULTS FROM X-RAY SPECTROSCOPY

Though exploratory surveys are essential for determining the general X-ray properties of the population as a whole, spectroscopic investigations are also required to obtain more detailed information on the X-ray continuum shape and absorption properties. Gallagher et al. (2002b) gathered together 8 spectroscopic-quality observations to investigate general trends from these data. In general, they found that the underlying X-ray continua are consistent with normal radio-quiet quasars, with significant, complex absorption. Possible sources of the observed complexity (illustrated in Figure 4) include partial covering of the X-ray continuum, ionized gas, and velocity structure similar to that seen in the UV regime. Furthermore, normalizing the power-law continua above 5 keV to correct for absorption resulted in typical radio-quiet quasar values of $\alpha_{\text{ox}}$. All of these results are consistent with the Murray et al. (1995) picture.

However, some unexpected results have also arisen. Among the most interesting is the observation of

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3The hardness ratio is defined as $HR = (h - s)/f$ where $h = 2–8$ keV counts, $s = 0.5–2.0$ keV counts, and $f = 0.5–8.0$ keV counts.
Fig. 3. **Left panel:** Hardness ratio versus $\alpha_{\text{ox}}$. The trend of increasing hardness ratio with decreasing $\alpha_{\text{ox}}$ is consistent with absorption as the primary cause of X-ray weakness in BAL quasars. **Right panel:** Minimum velocity of C iv absorption versus $\alpha_{\text{ox}}$. Contrary to expectations from the shielding gas models (§5, Murray et al., 1995), there is no apparent correlation between these parameters.

Fig. 4. Observed-frame ACIS-S3 spectrum of PG 1115+080. This spectrum has been fit with a power-law model above rest-frame 5 keV which has then been extrapolated back to lower energies. The significant negative residuals below $\sim 1.2$ keV indicate strong absorption, and the structure rules out simple absorption by neutral gas. While the nature of this complex absorber is not well-constrained, it is consistent with a high ionization parameter.

two absorption lines in the spectrum of APM 08279+5255, apparently from highly ionized Fe outflowing with speeds of $\sim 0.2$ and $\sim 0.4c$ (Chartas et al., 2002). In radiatively driven flows, such high terminal velocities occur in gas launched at much smaller radii than the UV BAL wind, which has terminal velocities of $\sim 12,000$ km s$^{-1}$. In addition, when compared with an XMM-Newton observation of this object taken $\sim 12$ rest-frame days later (Hasinger et al., 2002), there is a clear indication of variability in the absorber properties. APM 08279+5255 is not unique; similar absorption lines have also been seen in PG 1115+080 (Chartas et al., in prep.). These results are challenging for models in which the X-ray and UV absorption arise in the same medium and are predicted to have the same velocity structure (e.g., Elvis, 2000). Significant iron emission has also been observed in some objects including H 1413+117 (Oshima et al., 2001; Gallagher et al., 2002).

In another unanticipated result, the formerly X-ray brightest BAL quasar PG 2112+059 (Gallagher et al., 2001) exhibited significant variability between the ASCA observation of Oct 1999 and the Chandra observation of Sep 2002. In the most recent Chandra data, the power-law continuum normalization dropped by a factor of a few while the measured column density of the absorber increased significantly. Notably, concurrent HST STIS data of the C iv absorption line showed no large changes from earlier UV observations. For PG 2112+059 at least, evidence for distinct X-ray and UV absorbers is mounting.
IMPLICATIONS FOR THEORETICAL MODELS OF QUASAR OUTFLOWS

In general, X-ray studies are providing support for the family of radiatively driven wind models. BAL quasars are generally X-ray weak with values of $\alpha_{\text{ox}}$ indicating a significant reduction in observed X-ray flux relative to the UV continuum. When sufficient data are available, the intrinsic X-ray power, corrected for absorption, is typical of normal radio-quiet quasars. The complexity in the X-ray absorbers is consistent with highly ionized gas as predicted for the shielding gas; however the ionization state cannot be constrained given the current data quality.

Though the wind models have had some success, the lack of any apparent correlation between the UV absorption-line and X-ray properties is contrary to the model predictions. While certainly X-ray and UV absorption are found together in the same objects, the connection between the two is not straightforward. This is perhaps not unexpected given the complexity of the UV BALs and potential quasar-to-quasar variations in wind properties. The assertion of Elvis (2000) that the UV and X-ray absorption arise from the same medium is not easily reconciled with the lack of connection between X-ray and UV variability seen in PG 2112+059 and the mismatch in X-ray and UV absorption properties seen in APM 08279+5255. In addition, the large-velocity outflows seen in APM 08279+5255, which imply a much smaller launching radius that for the BAL gas, do not fit within the Elvis (2000) picture with a narrow range of launching radii for the outflow.

One of the problems for theoretical wind models with small launching radii is the lack of variability in velocity structure in the UV absorption lines on observed-frame timescales of years (e.g., le Kook, 1997). However, the most comprehensive absorption-line variability investigation to date, the 3 yr study of Barlow (1993), was not long enough for a conclusive test; the hydrodynamic wind models of Proga et al. (2000) generated instabilities on rest-frame timescales of $\sim 3$ yr. With longer time baselines, velocity increases have been seen for at least one object (Vilkoviskij and Irwin, 2001), and an extended study is certainly warranted to investigate this issue further. If the bulk of the X-ray absorbing gas is on smaller scales than the BAL gas, it is also possible that X-ray absorption variability on shorter timescales may regularly occur, as seen for PG 2112+059 and APM 08279+5255. To make accurate predictions for such events, the hydrodynamic models may need to be extended to smaller radii ($< 10^{15}$ cm) with higher resolution, and also more explicitly include the effects of Compton pressure. For highly ionized gas, this will dominate the radiation force (D. Chelouche, priv. comm.). Additional items for an X-ray observer’s wish list from theoretical modeling are specific predictions for the strength and profiles of Fe emission and absorption lines.

An outstanding issue for future investigations concerns the velocity of the X-ray absorbing gas in most BAL quasars; is it stalled, outflowing, or inflowing? Proga et al. (2000) claimed that highly ionized gas should be inflowing or stalled, but the evidence from APM 08279+5255 and PG 1115+080 suggests otherwise. An X-ray gratings observation of a BAL quasar offers the potential for a qualitative advance in this field. The improved resolution of gratings data, from $\Delta v \sim 20,000$ km s$^{-1}$ for CCD data to $< 1300$ km s$^{-1}$, would enable a more penetrating and subtle investigation into the connection between UV and X-ray absorption. In particular, significant constraints could be placed on the velocity, column density, and ionization state of the X-ray absorbing gas. These values can then provide information on the location of the X-ray absorber and the mass-outflow rate, parameters of fundamental physical importance.

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