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Probing 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 $\sim$ 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 them. 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.

1.1 Introduction

During the bulk of their accretion phases, supermassive black holes apparently reveal themselves as luminous quasars (e.g., Yu & Tremaine 2002), and thus quasar winds are likely to provide a primary source of feedback during the coeval growth of black holes and their hosts' galactic bulges. These winds are directly observed in the population of Broad Absorption Line Quasars (BALQs), $\sim$ 10% of the quasar population that exhibit deep, broad absorption lines from high-ionization UV resonance transitions. X-rays, generated in the innermost regions surrounding accreting black holes, travel through the nuclear environment to the observer. X-ray studies of BALQs thus offer a privileged view through the wind.

The challenge of accelerating gas to the high velocities observed in BALQs led Murray et al. (1995) to a picture similar to that presented in Figure 1.1. In this model, at radii starting at $\sim 10^{16}$ 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 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 launch the wind at such small distances, a thick layer of "shielding" gas, highly ionized plasma with $N_{\rm H} = 10^{22}$–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, & Kallman (2000), this layer of shielding gas arose naturally from the simulations. This scenario produces several predictions for X-ray observations of BALQs:

• BALQs 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.

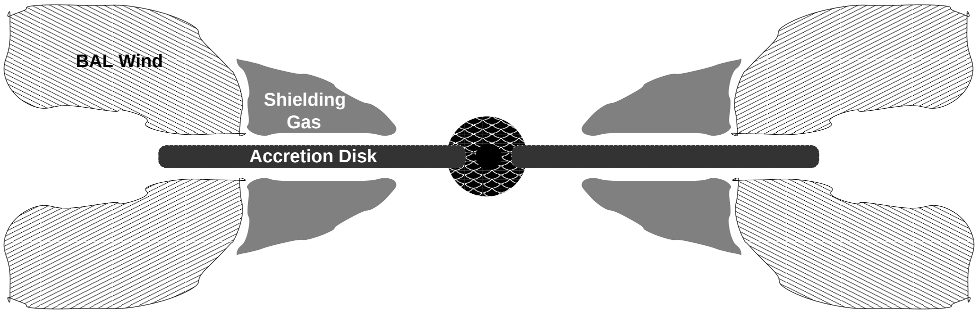

Fig. 1.1. Diagram of a possible geometry for the nucleus of a quasar based on the Murray et al. (1995) model. The patterned gray circle represents the X-ray emitting region surrounding the black hole.

• All BALQs should be X-ray weak, i.e., have values of $\alpha_{\rm ox} \lesssim -2.0$,* 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 $\alpha_{\rm ox}$ 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 BALQs 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 contribution, we briefly summarize the insights offered from both exploratory and spectroscopic X-ray surveys of BALQs to the understanding of quasar winds.

1.2 Results from X-ray Observations

Given the extreme faintness of BALQs in the soft X-ray regime (e.g., Green & Mathur 1996), obtaining detailed spectroscopic information requires a significant commitment of observatory time. Pursuing an alternate strategy of exploratory observations enables much larger numbers of BALQs to be observed with the goal of measuring X-ray flux, hardness ratio, and $\alpha_{\rm ox}$ 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 (Green et al. 2001; Gallagher et al. 2002b).

We are in the process of compiling the largest exploratory survey to date, with a well-defined sample of BALQs drawn from the Large Bright Quasar Survey (LBQS; Foltz et al. 1989; Hewett et al. 1995). This sample of $z > 1.35$ BALQs 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 $\alpha_{\rm ox}$ (Gallagher et al. 2002b, in prep.).

Though the BALQs in our sample are indeed weak in X-rays with a median value of $\alpha_{\rm ox} = -2.2$, they are generally detectable with the current generation of X-ray observatories. For those objects that are detected, a measurement of the hardness ratio indicates what frac-

* The quantity $\alpha_{\rm ox}$ 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 $\alpha_{\rm ox} = -1.56 \pm 0.14$ (Brandt et al. 2001).

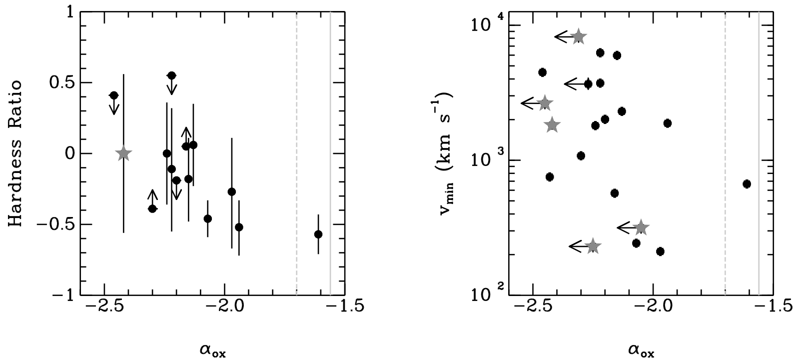

Fig. 1.2. **Left panel:** Hardness ratio versus α_{ox}. **Right panel:** Minimum velocity of C IV absorption versus α_{ox}.

tion 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 α_{ox} illustrated in Figure 1.2 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 α_{ox} can be used in a rough sense to indicate the extent of absorption. Following this premise, α_{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 BALQs. In this regime, there are no apparent correlations between α_{ox} and several absorption-line properties for the BALQs, most significantly the minimum velocity of C IV absorption shown in Figure 1.2. Furthermore, the large column densities of absorbing gas implied by values of $\alpha_{ox} \lesssim -2.0$ 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.

Though exploratory surveys are essential for determining the general X-ray properties of the BALQ 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. (2002a) gathered together 8 spectroscopic-quality observations to investigate trends. In general, they found that the underlying X-ray continua are consistent with those of normal radio-quiet quasars, with significant, complex absorption. Possible sources of the observed complexity include partial covering of the X-ray continuum, high ionization, 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 α_{ox}.

However, some unexpected results have also arisen. Among the most interesting is the observation of two absorption lines in the X-ray spectrum of APM 08279+5255, apparently from highly ionized Fe outflowing with speeds of ~ 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 ~ 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.).

In another unanticipated result, the formerly X-ray brightest BALQ 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 spectra.

1.3 Theoretical Implications

In general, X-ray studies are providing support for the family of radiatively driven wind models. BALQs are generally X-ray weak with values of $\alpha_{\rm ox}$ 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 not in line with simple 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 X-ray and UV 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 velocities seen in APM 08279+5255. In addition, the large-velocity outflows seen in APM 08279+5255, which imply a much smaller launching radius than 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 of the UV absorption lines on observed-frame timescales of years (e.g., de Kool 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 ~ 3 yr. If the bulk of the X-ray absorbing gas is on smaller scales than the BAL gas, it is 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.).

An outstanding issue for future investigations concerns the velocity of the X-ray absorbing gas in most BALQs; 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 BALQ 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 X-ray absorbers. 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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