Stratified Quasar Winds: Integrating X-ray and Infrared Views of Broad Absorption Line Quasars

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Abstract. Quasars are notable for the luminous power they emit across decades in frequency from the far-infrared through hard X-rays; emission at different frequencies emerges from physical scales ranging from AUs to parsecs. Each wavelength regime thus offers a different line of sight into the central engine and a separate probe of outflowing material. Therefore, obtaining a complete accounting of the physical characteristics and kinetic power of quasar winds requires a panchromatic approach. X-ray and infrared studies are particularly powerful for covering the range of interesting physical scales and ionization states of the outflow. We present a stratified wind picture based on a synthesis of multiwavelength research programs designed to constrain the nature of mass ejection from radio-quiet quasars. This wind comprises three zones: the highly ionized shielding gas, the ultraviolet broad absorption line wind, and the cold dusty outflow. The primary launching mechanism for the wind likely varies in each zone. While radiative acceleration on resonance lines dominates for the ultraviolet absorbing wind, the shielding gas may instead be driven by magnetic forces. Ultraviolet continuum radiative pressure, perhaps coupled with magnetic launching, accelerates a dusty outflow that obscures the inner broad line region in unification schemes.

1. Introduction

Theoretical modeling of structure formation in a Λ-CDM cosmology cannot match observed galaxy luminosity functions locally unless some form of heating or “feedback” is included in the simulations (e.g., Granato et al. 2004). This strong theoretical requirement coupled with (1) the empirical discoveries of the strong correlations between black hole masses and the properties of their galactic bulges (e.g., Ferrarese & Merritt 2000; Gebhardt et al. 2000) and (2) the observation that growing supermassive black holes reveal themselves as luminous quasars (e.g., Soltan 1982; Yu & Tremaine 2002) have led to quasar winds becoming promising sources of feedback in massive (> $L^*$) galaxies (e.g., Silk & Rees 1998). Attempts to model these outflows in cosmological simulations currently employ simplifying and inaccurate assumptions without incorporating empirical constraints. Quasar winds are directly observed in Broad Absorption
Line (BAL) quasars; this $\sim 15\text{--}20\%$ of the luminous, radio-quiet quasar population exhibits deep troughs from high-ionization ultraviolet resonance transitions such as C $\text{iv}$ and O $\text{vi}$. Such absorption features appear blueshifted along lines of sight passing through winds with terminal velocities reaching $0.03\text{--}0.3c$.

Constraining the nature of quasar outflows, including the geometry, acceleration mechanism, ionization state, and mass outflow rate, is fundamental both for understanding the role of quasars in galaxy evolution as well as accretion physics. Quasars are by nature multiwavelength, and a complete accounting of the outflow requires a panchromatic approach.

2. Empirical Constraints on Wind Properties

BAL quasars have been the targets of surveys at all wavelengths. As the sensitivity of available facilities increases over time, the empirical data on distinct outflow components have become more constraining. Below, we briefly summarize the conclusions and implications from studies in three regimes, the ultraviolet, the X-ray, and the infrared; these results are compiled in Table 1. Constraints on the launching radius ($R_{\text{launch}}$), covering fraction ($f_{\text{cov}}$), column density ($N_{\text{H}}$), and velocity ($v$) of the wind probed in these regimes is of particular interest for determining the structure and kinetic energy of the flow.

2.1. The Ultraviolet Line-Driven Wind

BAL quasars by definition show outflows in the ultraviolet, and there is compelling evidence that these are radiatively driven. The momentum from photons absorbed from the quasar continuum is sufficient to push gas to the high observed velocities of up to $10^{4.5}$ km s$^{-1}$ (e.g., Murray et al. 1995; de Kool 1997). In fact, the BAL absorption features represent photon momentum absorbed from the ultraviolet continuum. In addition, line-locked systems detected in some objects provide direct evidence for the importance of line driving (e.g., Braun & Milgrom 1989). Stable absorption-line locking occurs when the relative Doppler shift of gas at different distances from the continuum source is approximately equal to the wavelength separation of two strong absorption lines (e.g., Ly$\alpha$ and N $\text{v}$). These systems then become locked into approximately this velocity separation, with the system closer to the continuum source absorbing the photons that would otherwise continue to accelerate the more distant, higher velocity system (e.g., Scargle 1973). Line-locked systems do not occur unless line-driving plays an important role in the dynamics of the outflow (e.g., Korista et al. 1993; Arav 1999; Chelouche & Netzer 2003). In fact, the line-locked transitions themselves have to play an important role in the dynamics for line-locking to operate.

The geometry most frequently associated with BAL outflows is equatorial (e.g., de Kool & Begelman 1995; Murray et al. 1995), and spectropolarimetry of BAL and non-BAL quasars supports this generic picture (e.g., Ogle et al. 1999). In this scenario, the material in the wind originates in the accretion disk. Some vertical pressure, either thermal, magnetic, or radiative, pushes gas upwards, to be illuminated by the continuum emission generated at smaller radii. Radiation pressure then accelerates the gas radially; this is most efficient when the photon energies match those of strong resonance atomic transitions. The covering
fraction of the outflow in this picture is determined by the ratio of the (vertical) disk pressure to the (radial) central continuum pressure. As ultraviolet emission lines are often absorbed, the BAL wind must be outside of, or perhaps co-spatial with, the broad emission line (BEL) region. Using the $L_{UV} - R_{CIV}$ reverberation mapping relationship measured by Kaspi et al. (2007), the C IV BEL region radius is $\sim 2 \times 10^{17}$ cm for a luminous ($\lambda L_{1350 \AA} = 10^{46}$ erg s$^{-1}$) quasar. For a BEL region at the base of the outflow, the C IV BAL radius is approximately the same (Murray & Chiang 1998).

As mentioned above, because the ultraviolet continuum generates the radiative pressure on the BAL gas, the distance between the continuum and the BAL gas will ultimately affect the covering fraction of the wind. This is an area where important observational constraints can perhaps be brought to bear. Though $\alpha$-disk models predict that $\sim 90\%$ of the optical/ultraviolet continuum is generated within $7 \times 10^{15}$ cm for $M_{\rm BH} = 3 \times 10^8 M_\odot$, recent constraints from microlensing of quasar accretion disks suggests the continuum emitting region is actually significantly larger, $\sim 5 \times 10^{16}$ cm (Pooley et al. 2006; Kochanek et al. 2007).

### 2.2. The Shielding Gas

At first glance, a quasar appears well-suited to radiative gas acceleration given the strong ultraviolet radiation field. However, unlike O stars, quasars are also strong X-ray sources. This high flux of X-ray photons ionizes the wind, thus eliminating ultraviolet resonance lines. Highly ionized gas can only be driven radiatively by radiation pressure on electrons, which is much less efficient than resonance line pressure. To prevent overionization, some material is needed to protect the wind from the ionizing far-ultraviolet and X-ray continuum (Shlosman, Vitello, & Shaviv 1985). In the context of continuous winds, a layer of shielding gas was hypothesized by Murray et al. (1995; who dubbed it “hitchhiking gas”) as a thick, highly ionized layer of gas interior to the ultraviolet BAL wind. Their model required shielding gas in order to launch the wind from small radii ($\sim 10^{16}$ cm). Though initially introduced in a rather ad hoc manner, the empirical evidence for the existence of the shielding gas has become quite compelling. In particular, measurements of the column density of X-ray absorbing gas in radio-quiet BAL quasars find a range of $N_{\rm H} = 10^{22} - 10^{24}$ cm$^{-2}$ (e.g., Green et al. 2001; Gallagher et al. 2002). These values are one to two orders of magnitude larger than the best constraints from careful modeling of the ultraviolet absorption lines (e.g., Arav et al. 2001). This discrepancy is most dramatic in the BAL quasars whose extreme X-ray weakness indicates they are likely to host Compton-thick ($N_{\rm H} > 1.5 \times 10^{24}$ cm$^{-2}$) absorbers.

To date, Compton-thick absorption has only been confirmed for one BAL quasar, Mrk 231, with the detection of its direct continuum above 10 keV by Braito et al. (2004); at softer X-ray energies only scattered and starburst emission is seen. Notably, the putative X-ray Compton-thick BAL quasars show broad emission lines and often blue ultraviolet-optical continua (e.g., Clavel et al. 2006; Gallagher et al. 2006). As first seen by Green et al. (2001), the $\sim 10\%$ of BAL quasars with low-ionization (Mg II) BALs may typically have Compton-thick X-ray absorbers, and Gallagher et al. (2006) speculated that Mg II BALs might require such X-ray absorption for the low-ionization gas to exist in the outflow. The converse is not true, however, and so Compton-thick X-
ray absorbers may be a necessary but not sufficient condition for low-ionization BALs.

Given that an absorber with $N^\text{H} > 1.5 \times 10^{24} \text{ cm}^{-2}$ is optically thick to the ultraviolet/X-ray continuum in a quasar, such X-ray absorbers must not fully cover the ultraviolet continuum-emitting region. Though a (less than Compton-thick) highly ionized shielding gas component might be expected to allow a significant ultraviolet photon flux through the wind (Murray et al. 1995), radiative transfer calculations of highly ionized magneto-hydrodynamic (MHD) disk winds hint that some less ionized gas would still be present to block a large fraction of the ultraviolet flux (Everett 2005). This implies that the ultraviolet BAL wind lies along a distinct path to the ultraviolet continuum in these systems compared to the absorber blocking the X-ray continuum. If this is generically true (though only evident for the most extreme examples), this result provides an important constraint on the relative location of the ultraviolet and X-ray continuum sources. For an X-ray continuum generated on smaller spatial scales than the ultraviolet, as implied by recent constraints from microlensing (Pooley et al. 2006; Kochanek et al. 2007), a stratified wind can account for discrepancies in the ultraviolet and X-ray absorber properties. We explore this further in §4.

To date, the best evidence from X-ray spectral modeling indicates that the absorbers are plausibly highly ionized such that the soft X-ray opacity would be dominated by O vii and O viii absorption edges. Strong X-ray absorption variability unmatched by changes in the ultraviolet BALs also points towards distinct ultraviolet and X-ray absorbing material (e.g., Gallagher et al. 2004) with the X-ray absorber closer than the ultraviolet absorber to the central X-ray continuum. The bulk of the X-ray data to date thus support the identification of the X-ray absorber with the putative shielding gas.

The recent discovery of a correlation between the maximum terminal velocity of the ultraviolet BAL (as measured for C iv), $v_{\text{max}}$, and X-ray weakness in BAL quasars indicates the importance of shielding in the outflow (Gallagher et al. 2006). Without enough signal in this exploratory survey for spectral fitting, X-ray weakness was taken to indicate strong X-ray absorption. It is a generic property of gas escaping from the vicinity of the black hole that the terminal velocity will be of order the Keplerian velocity of the radius from which it was launched. Gas that obtains the highest velocities then might have originated at the smallest radii where the photon densities are highest. However, radiative line-driving is only efficient if the gas does not become overionized; this can be accomplished with a thick layer of shielding gas. This scenario might explain the correlation between extreme X-ray weakness and the highest values of $v_{\text{max}}$. Figure 1 shows a schematic of this situation.

To date, the largest unknown in the properties of the shielding gas is its velocity. For the bulk of BAL quasars with X-ray spectra, the velocity cannot be measured with the current generation of observatories; only a handful are bright enough in X-rays to search for X-ray BALs. Two BAL quasars with putative Fe XXV BALs, PG1115+080 and APM08279+5255, indicate high (tenths of c) blueshifts (Chartas et al. 2007), however, the frequency of such features is unknown.
Figure 1. Two diagrams of the inner part of the accretion disk illustrating the possible connection between the presence of X-ray shielding gas (solid shape) and the velocity of the ultraviolet BAL outflow (solid curves). In both panels, the black hole is to the right, and the continuum emission is generated in the accretion disk. The horizontal white bar serves as a scale marker, and the size of the arrows corresponds to the velocity of the outflowing BAL gas. Left: In this case, a thin shield does not allow gas to be accelerated until larger radii. Right: A thick shield prevents overionization of the ultraviolet BAL wind at smaller radii where the higher photon densities allow the material to be launched to larger terminal velocities. A larger vertical contribution from the accretion disk radiation can also change the covering fraction of the outflow.

2.3. Dusty Outflows

Outflows may exist on larger scales, as well. Königl & Kartje (1994) first proposed that the so-called “dusty torus” – the structure consisting of cold material on parsec scales that reprocesses direct accretion power into thermal infrared emission – is actually an outflow. In their model (applied to Seyfert galaxies), the wind is uplifted vertically from the accretion disk along magnetic field lines as a magneto-centrifugally launched outflow (as in, e.g., Blandford & Payne 1982; Emmering, Blandford, & Shlosman 1992; Bottorff et al. 1997). At large launching radii, dust can survive in this outflow, and when this dusty gas attains a sufficient vertical height, it becomes illuminated by the central ultraviolet continuum. At that point, radiation pressure accelerates the dusty gas radially outward, flattening the wind. This elegant model avoids problems with explaining the torus as a large ring of (clumpy) cold material in the center of the galaxy; such gas is dynamically unstable and will collapse (c.f., Krolik & Begelman 1988).

While the role of magnetic fields in driving quasar outflows remains to be observationally constrained, ultraviolet photons certainly will efficiently accelerate dust grains. The inner wall of this dusty outflow is set by the temperature at which refractory dust grains (likely graphites) sublimate, $T_{\text{sub}} \sim 1500$ K. As the dust is heated by the radiant power of the quasar continuum, the sublimation radius, $R_{\text{sub}}$, is proportional to $L_{\text{UV}}^{0.5}$ (Barvainis 1987). For a quasar with $L_{\text{UV}} \sim 10^{46}$ erg s$^{-1}$, the inner wall of the dusty outflow is at 1–2 pc. At these radii, the supermassive black hole will dominate the dynamics of the gas, and the Keplerian velocity is $\sim 10^3$ km s$^{-1}$. The velocity dispersion of the bulge of a massive host galaxy, 200–300 km s$^{-1}$, provides a plausible lower bound to the velocity of this material.
BAL quasar ultraviolet spectra typically show evidence for reddening and extinction in comparison with non-BAL quasars (Sprayberry & Foltz 1992; Reichard et al. 2003), and this could be taken to imply that some part of this dusty outflow is perhaps just the outer regions of the ultraviolet BAL wind. However, a recent study of 9.7µm silicate features in infrared quasar spectra by Shi et al. (2006) found that BAL quasars typically show very prominent silicate emission. This is in contrast to type 2 (narrow emission line) Seyfert galaxies which usually show strong silicate absorption, as predicted by Königl & Kartje (1994) and others. The detection of silicate emission in BAL quasars indicates that the dusty outflow therefore is distinct from the ultraviolet BAL wind. If the silicate grains (at $T_{\text{sil}} \sim 200$ K; Hao et al. 2005) were instead carried in the BAL wind, the line of sight to the infrared continuum source generated by the warmer dust at smaller radii would pass through the silicate region. In this case, silicate absorption is expected.

Within the unified quasar picture, some fraction of the sky is obscured by the dusty outflow such that the broad emission line region and central continuum are hidden from the direct line of sight. In this case, the ratio of type 2 to type 1 (broad emission line) quasars gives the value for the covering fraction of the dusty outflow (e.g., Richards et al. 2006).

### Properties of the Stratified Quasar Wind

| Wind Component             | $R_{\text{launch}}$ (cm) | $f_{\text{cov}}$ | $N_H^a$ (cm$^{-2}$) | $v$ (km s$^{-1}$) | $\text{ion. state}^b$ |
|----------------------------|--------------------------|------------------|---------------------|------------------|------------------|
| Shielding Gas              | $10^{15}$–$10^{16}$      | > $f_{\text{cov, UV}}$ | $10^{22}$–$10^{24}$ | O VII, O VIII | ? |
| UV BAL Wind                | $10^{17}$                | 0.2(1 $- f_{\text{type2}}$) | $10^{21}$–$10^{22}$ | C IV, O VI | $10^3$–$10^4$ |
| Dusty Outflow              | $10^{18.5}$              | $f_{\text{type2}}$ | ... | neutral | $10^2$–$10^3$ |

aLine-of-sight column density. bCommon ions representing the ionization state.

### 3. The Role of Winds

In the simplest disk-wind paradigm, all quasars host outflows, but only in BAL quasars are these driven along the line of sight. Therefore, the fraction of type 1 quasars with BALs, $\sim 15$–$20\%$ (Reichard et al. 2003; Hewett & Foltz 2003), corresponds to the covering fraction of the BAL wind. The opposite case would be that only a subset of quasars host BAL winds, but these dusty shrouds cover a large fraction of the sky – the “cocoon” picture (e.g., Becker et al. 2001). In this latter situation, BAL quasars would be expected to be mid-infrared bright relative to non-BAL quasars with little or no wind because a larger fraction of the accretion power is captured and reprocessed into the thermal infrared by dust. The recent Spitzer survey of 38 BAL quasars by Gallagher et al. (2007) disputes this latter view, as they found that the mid-infrared properties of BAL quasars are consistent with non-BAL quasars of comparable luminosity. In particular, the relative power in the optical and mid-infrared in the two populations is indistinguishable. Coupled with clear evidence from spectropolarimetry that there are lines of sight to BAL quasars that are not covered by the ultraviolet outflow (e.g., Ogle et al. 1999), it seems quite likely that most luminous quasars host BAL outflows, and only in BAL quasars are we actually looking through them (Weymann et al. 1991).
Though the first ultraviolet spectroscopic comparisons of the emission-line and continuum properties of BAL versus non-BAL quasars found them to be “remarkably similar” (Weymann et al. 1991), spectral studies with much larger samples revealed that BAL are more often found in quasars with intrinsically blue ultraviolet-optical continua and broader emission lines (Richards et al. 2002). We point out that the covering fraction of the wind in any given quasar is likely to vary, and so those quasars with the largest covering fractions are most likely to be identified as BAL quasars. This will skew the “average” continuum and emission-line properties of BAL quasars to be representative of quasars with more substantial outflows, rather than the typical outflow. A discussion of possible links between active winds, continuum properties, and ultraviolet emission-line properties is presented in Richards (2006).

4. Constructing a Consistent Geometry

Based on the empirical constraints outlined in §2, we construct the diagram of the stratified wind presented in Figure 2 with approximately three zones: the shielding gas, the ultraviolet BAL wind, and the dusty outflow. Each zone is spatially distinct and can be characterized by distinct covering fractions, column densities, ionization states, and probably velocities. The acceleration mechanisms also differ. While there is compelling evidence that radiative line pressure dominates for the ultraviolet BAL wind, the dynamical state of the shielding gas remains uncertain. For gas characterized by atomic species from O vii up to Fe xxv, the gas is too ionized for line driving to be effective, and X-ray continuum driving is also insufficient (Everett & Ballantyne 2004). Therefore, if the shielding gas velocities are typically \( \sim 0.1c \) as seen in the two known cases of X-ray BALs, MHD forces are likely to dominate the acceleration. However, the shielding gas might instead be stalled or even infalling (Proga et al. 2000). Meanwhile, for the dusty outflows on large scales, ultraviolet continuum pressure on dust grains overrides electron continuum pressure by approximately a factor of 850 (Königl & Kartje 1994). Efficient acceleration combined with the large launching radius for the dusty component make it the most equatorial part of the outflow in a luminous quasar.

Observationally, panchromatic observations are very important in constructing this picture, as each wind component is viewed primarily in a distinct portion of the spectral energy distribution. While the X-ray continuum is imprinted by both the shielding gas and the ultraviolet BAL wind, the larger column density of the shielding gas makes its effect more pronounced. The ultraviolet continuum is likely not completely covered by the shielding gas, which in any case is highly ionized and would be nearly invisible in the ultraviolet for \( N_H \ll 10^{24} \text{ cm}^{-2} \). The BALs affecting the ultraviolet continuum are the clear signatures of this component. The dusty outflow, meanwhile, is detected and probed via its infrared emission in luminous BAL quasars.

We emphasize that this proposed picture is based on empirical data for luminous, radio-quiet BAL quasars. Outflows in both lower luminosity Seyfert galaxies and radio-loud quasars are likely to be qualitatively distinct because of differences in both luminosity and spectral energy distributions. Specifically, Seyfert galaxies and radio-loud quasars emit a larger fraction of their radiant power.
in the X-rays than luminous radio-quiet quasars (e.g., Brinkmann et al. 1997; Steffen et al. 2006). As discussed by Murray et al. (1995), X-ray loud active galactic nuclei will have difficulty launching radiatively driven winds. These differences in wind driving are observationally supported: for instance, the ultraviolet absorbing outflows in the lower luminosity Seyfert galaxy NGC 4151 are likely MHD-driven (Crenshaw & Kraemer 2007). In addition, magneto-centrifugally dominated wind models have successfully fit emission line variations in the Seyfert 1 galaxy NGC 5548 (Bottorff et al. 1997); these models also yield a stratified wind structure (Bottorff, Korista, & Shlosman 2000).

5. Conclusions

Figure 2 is a schematic, simplified view of the stratified wind drawn in an attempt to incorporate the growing body of multiwavelength data as well as modeling of disk winds from the past decade or so. As such, it requires further theoretical and empirical elaboration. For example, the outflowing (magneto-centrifugal) wind is likely to be clumpy, as suggested by comparisons of models with observations (Nenkova et al. 2002; Elitzur & Shlosman 2006). Furthermore, the shielding gas is probably not discontinuous from the ultraviolet BAL wind, but is instead the highly ionized inner region (e.g., Königl & Kartje 1994; Murray et al. 1995; Bottorff, Korista, & Shlosman 2000; Proga et al. 2000; Everett 2005).

Outflows are most easily studied in BAL quasars where the absorbing gas is obviously along the line of sight. However, there should be signatures of outflows in non-BAL quasars if the disk-wind paradigm is generally correct. For example, X-rays absorbed by the shielding gas will be emitted along other lines of sight; this contribution to non-BAL quasar X-ray spectra at soft energies will depend on the covering fraction and geometry of the shield. In this case, high signal-
to-noise X-ray spectroscopy may reveal a variable scattered light component in luminous type 1 quasars.

In the near future, high quality near and mid-infrared spectra will offer new insights into the hottest dust at the inner boundary of the dusty outflow. Furthermore, in-depth analysis of solid state features such as 9.7 and 18 \( \mu m \) silicate emission can provide constraints on dust processing and perhaps grain formation within the quasar environment.

At present, it appears that neither the dusty outflow nor the ultraviolet BAL wind carries sufficient kinetic luminosity to account for the feedback required to affect galaxy evolution. The shielding gas, with its high column density and currently unknown velocity, is therefore the most promising component to dominate the energetics. Constraining these velocities will require the high spectral resolution and large effective area of the next generation of X-ray observatories such as Constellation-X, as well as continued modeling efforts that incorporate all phases of the outflow.

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