X-raying the Winds of Luminous Active Galaxies

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Abstract. We briefly describe some recent observational results, mainly at X-ray wavelengths, on the winds of luminous active galactic nuclei (AGNs). These winds likely play a significant role in galaxy feedback. Topics covered include (1) Relations between X-ray and UV absorption in Broad Absorption Line (BAL) and mini-BAL quasars; (2) X-ray absorption in radio-loud BAL quasars; and (3) Evidence for relativistic iron K BALs in the X-ray spectra of a few bright quasars. We also mention some key outstanding problems and prospects for future advances; e.g., with the International X-ray Observatory (IXO).

Keywords: Active Galactic Nuclei (AGNs), Quasars, Black Holes, AGN Winds, X-ray spectroscopy, X-ray absorption, Absorption lines

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THE RANGE OF AGN OUTFLOWS AND THE RELEVANCE OF X-RAY ABSORPTION STUDIES

Fast winds that absorb X-ray and UV radiation are commonly seen in active galactic nuclei (AGNs) spanning a range of \( \approx 100,000 \) in luminosity. These outflows are a substantial component of AGN nuclear environments, and their ubiquity argues that mass ejection in a wind is fundamentally linked to mass accretion. In luminous AGNs, such as Broad Absorption Line (BAL) and mini-BAL quasars, wind velocities can be very high (up to \( \approx 0.15c \)), and these winds may carry a significant fraction of the accretion power and be responsible for effective feedback into AGN host galaxies. In this proceedings paper, we will briefly review a few recent results on X-ray studies of BAL and mini-BAL quasars and also discuss some prospects for future advances.

One frequently used and well-motivated model proposes that the UV absorption lines of BAL and mini-BAL quasars originate in a line-driven wind that is launched from the accretion disk at \( \approx 10^{16} \) cm from the black hole (e.g., Murray et al. 1995; Proga & Kallman 2004). In this model, the apparently weak X-ray emission often seen from these quasars is caused by X-ray absorption (with \( N_H \approx 10^{22} \)–\( 10^{24} \) cm\(^{-2} \)) in highly ionized “shielding gas” at smaller radii that protects the wind from nuclear EUV and soft X-ray radiation. Without this critical absorbing layer, these energetic photons would over-ionize the UV-absorbing gas so that it could not be radiatively accelerated effectively.
SOME RECENT X-RAY RESULTS ON LUMINOUS AGN WINDS

Statistical X-ray Studies of BAL and Mini-BAL Quasars

As mentioned above, X-ray absorption processes are likely critical to allowing wind driving and BAL formation, and thus one might expect to observe relations between the X-ray and UV absorption properties of BAL and mini-BAL quasars. Evidence for such relations has been put forward in the past (e.g., Laor & Brandt 2002; Gallagher et al. 2006). In order to extend these studies, we have recently performed statistical analyses of BAL and mini-BAL quasars from the Sloan Digital Sky Survey (SDSS) that also have (mostly serendipitous) sensitive X-ray coverage from *Chandra* and *XMM-Newton* (Gibson et al. 2009ab); this work has been enabled by the large numbers of SDSS BAL and mini-BAL quasars that have now been cataloged (e.g., Gibson et al. 2009a). Most of our analyses have utilized 42 high-ionization BAL quasars, 8 low-ionization BAL quasars, and 48 high-ionization mini-BAL quasars (all are radio-quiet objects). These have been selected to have high-quality SDSS spectra and redshifts of $z = 1.68–2.28$, providing coverage of both C IV and Mg II (the most common high-ionization and low-ionization BALs, respectively).
Utilizing measurements of $\alpha_{\text{ox}}$ and $\Delta\alpha_{\text{ox}}$, we confirm past findings that low-ionization BAL quasars are even X-ray weaker than high-ionization BAL quasars, supporting the idea that remarkably heavy (and sometimes Compton-thick with $N_{H} \gtrsim 10^{24}$ cm$^{-2}$) X-ray absorption is often present in quasars with low-ionization BALs. This remains the strongest connection found between X-ray and UV absorption properties for BAL quasars. We also find that the level of X-ray weakness for mini-BAL quasars is intermediate between that of BAL and non-BAL quasars, supporting the idea that BAL and mini-BAL absorption are physically related phenomena.

We have found significant correlations, though with considerable scatter, between the level of X-ray weakness ($\Delta\alpha_{\text{ox}}$) and (1) the C IV absorption EW in broad troughs (see Fig. 1a), (2) the maximum observed C IV outflow velocity ($v_{\text{max}}$), and (3) the velocity width of C IV absorption. These correlations indicate that the strength of X-ray absorption is indeed affecting the formation and acceleration of the UV outflow, with stronger and faster UV outflows generally requiring more X-ray absorption. This is broadly consistent with the expectations of models for BAL quasars that include a line-driven disk wind plus shielding gas. The above being said, however, we have identified a subset of mini-BAL quasars that have large $v_{\text{max}}$ values (15,000–30,000 km s$^{-1}$) yet show no evidence for heavy X-ray absorption. Thus, while X-ray absorption generally promotes a strong and high-velocity UV outflow, it is perhaps not always required. Some other launching mechanism, perhaps magneto-rotational, could be responsible for accelerating the outflows of this subset of mini-BAL quasars.

Our data also extend some of the findings of Laor & Brandt (2002) and Ganguly et al. (2007) on the “envelope” of $v_{\text{max}}$ as a function of optical/UV luminosity, $L_{2500 \text{ Å}}$ (see Fig. 1b). Specifically, BAL quasars with higher values of $v_{\text{max}}$ (i.e., lying closer to the envelope) generally show stronger X-ray absorption. This extends the basic findings from Laor & Brandt (2002), which were based upon Palomar-Green quasars, upward in luminosity by about an order of magnitude. Improved source statistics are now needed to explore the $v_{\text{max}}$-$L_{2500 \text{ Å}}$-$\Delta\alpha_{\text{ox}}$ parameter space thoroughly, and these should be coming soon (see below).

An X-ray Survey of Bright, Representative Radio-Loud BAL Quasars

We have recently completed a systematic Chandra study of the X-ray properties of 21 radio-loud BAL quasars (12 new and 9 archival observations; Miller et al. 2009). Our new Chandra snapshot observations targeted the optically brightest radio-loud BAL quasars found in SDSS Data Release 3. A key goal of this work was to assess if radio-loud BAL quasars, which have both highly collimated relativistic jets as well as less-collimated winds, show similar X-ray absorption properties to those of radio-quiet BAL

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1 $\alpha_{\text{ox}}$ is defined to be the slope of a power law connecting the rest-frame 2500 Å and 2 keV monochromatic luminosities; i.e., $\alpha_{\text{ox}} = 0.3838 \log(L_{2 \text{ keV}}/L_{2500 \text{ Å}})$. This quantity is well known to be correlated with $L_{2500 \text{ Å}}$. We also define $\Delta\alpha_{\text{ox}} = \alpha_{\text{ox}}(\text{Observed}) - \alpha_{\text{ox}}(L_{2500 \text{ Å}})$, which quantifies the observed X-ray luminosity relative to that expected from the $\alpha_{\text{ox}}$-$L_{2500 \text{ Å}}$ relation; $\Delta\alpha_{\text{ox}}$ is useful for assessing the relative level of X-ray weakness.
FIGURE 2. X-ray (2 keV) vs. optical/UV (2500 Å) monochromatic luminosity (logarithmic) for BAL quasars as compared to non-BAL quasars. Panel (a) shows radio-loud BAL and non-BAL quasars (see symbol key). The solid and dotted lines in this panel show best-fit relations for non-BAL radio-loud and radio-quiet quasars, respectively. Panel (b) shows radio-quiet BAL and non-BAL quasars (see symbol key). The solid and dotted lines in this panel show best-fit relations for non-BAL radio-quiet quasars, while the dashed line shows the best-fit relation for non-BAL radio-loud quasars. Note, from comparing panels (a) and (b), that radio-loud BAL quasars are X-ray depressed relative to radio-loud non-BAL quasars, but not to the same degree as radio-quiet BAL quasars relative to radio-quiet non-BAL quasars. From Miller et al. (2009); see this paper for further explanation.

We find that the apparent X-ray luminosities of radio-loud BAL quasars are depressed by factors of \(\approx 4–9\) compared to those of radio-loud non-BAL quasars that are matched in optical/UV luminosity (see Fig. 2a); similar results are found when controlling for radio luminosity or both optical/UV and radio luminosity. This result is consistent with the presence of significant X-ray absorption in radio-loud BAL quasars. However, the degree of depression is typically less than that found when radio-quiet BAL quasars are compared to radio-quiet non-BAL quasars (see Fig. 2b). We also find a broad range of X-ray hardness ratio for radio-loud BAL quasars, and there is no clear correlation between hardness ratio and the degree of X-ray weakness. Such a correlation is found for radio-quiet BAL and mini-BAL quasars (e.g., Gallagher et al. 2006; Gibson et al. 2009b), as expected when absorption causes both spectral hardening and decreased apparent luminosity.

2 The hardness ratio is defined as \(\frac{(H - S)}{(H + S)}\), where \(H\) and \(S\) are the hard-band (2–8 keV) and soft-band (0.5–2 keV) counts, respectively.
FIGURE 3. Residuals from fitting (a) Chandra and (b) XMM-Newton spectra of the BAL quasar APM 08279+5255 with a power-law plus Galactic absorption model (data from 4.5–10 keV are used in the fitting). The residuals are in units of sigma with error bars of size unity. Note that highly significant residuals from 1.5–3.5 keV, corresponding to 7.5–17 keV in the rest frame, are detected in all spectra. From Chartas et al. (2009); see this paper for further explanation.

We have used our constraints upon X-ray luminosity and spectral shape to examine quantitatively physical models for the X-ray emission of radio-loud BAL quasars. The most natural and straightforward interpretation of our results is that radio-loud BAL quasars have both X-ray absorbers linked with winds (as for radio-quiet BAL quasars) as well as sub-pc-scale X-ray emitting jets. Much, but likely not all, of the X-ray emission from the jet occurs on physical scales larger than that of the X-ray absorber. This unabsorbed jet-linked X-ray emission somewhat dilutes the X-ray absorption signal relative to what is seen for radio-quiet BAL quasars. Our basic model indicates that the X-ray absorber and the sub-pc-scale X-ray emitting jet must have roughly comparable sizes, and it is also broadly supported by our high-quality X-ray data on the bright radio-loud BAL quasar PG 1004+130 (Miller et al. 2006).

X-ray Iron K BALs from Relativistic Outflows?

The kinetic luminosity of an AGN outflow, $L_{\text{kin}}$, is proportional to $f_c r (\frac{\Delta r}{r}) N_H v^3$, where $f_c$ is its global covering factor, $r$ is its radius, $\Delta r$ is its thickness, $N_H$ is its column density, and $v$ is its velocity. Since the column density of the X-ray absorber in BAL quasars is generally large ($N_H \approx 10^{22}–10^{24}$ cm$^{-2}$), this absorber could dominate the kinetic luminosity and mass-outflow rate if it is outflowing at about the velocity of the UV absorber (as is the case for local Seyfert galaxies) or higher. Unfortunately, however, the high-quality X-ray spectroscopic measurements of luminous quasars required for assessment
of absorption kinematics are challenging with current observatories. Therefore, the kinematic state of the X-ray absorber, and its relevance for AGN feedback into galaxies, is only now starting to become known for luminous quasars.

In 2002, we proposed that a relativistic outflow was responsible for creating remarkable 8–12 keV (rest-frame) absorption features seen in a Chandra spectrum of the luminous and gravitationally lensed BAL quasar APM 08279+5255 ($z = 3.91$; Chartas et al. 2002). These features were best fit by absorption lines, so we proposed that they were X-ray BALs from iron K transitions. The implied (projected) velocity, even for highly ionized iron (the most conservative assumption), was remarkably large with $v \approx 0.2–0.4c$; this is much higher than the velocity of the UV BALs in this quasar. The implied mass-outflow rate and kinetic luminosity are $\sim 10–30 M_\odot \text{yr}^{-1}$ and $L_{\text{kin}} \sim 10^{47} \text{erg s}^{-1}$ for reasonable estimates of $f_c$, $r$, $\Delta r$, and $N_H$. While the theoretical mechanisms for launching such a powerful outflow have not been worked out in detail, magneto-rotational or radiative processes could plausibly provide the requisite driving. The observed absorption features were detectable from APM 08279+5255 only due to its large gravitational lensing boost and high redshift, and such features could be present but undetected in the limited signal-to-noise spectra of many other distant BAL quasars.

Since remarkable claims require remarkable evidence, we have been working to acquire additional spectra for APM 08279+5255 with one primary goal being to test the model outlined in the previous paragraph. We now have 2 Chandra, 3 XMM-Newton, and 3 Suzaku spectra of APM 08279+5255, and the relevant absorption features are consistently detected in all 8 observations (see Fig. 3; Chartas et al. 2009; Saez, Chartas, & Brandt 2009). The features easily satisfy reasonable thresholds for significant detections, apparently unlike the case for some claimed relativistic narrow absorption lines (cf. Vaughan & Uttley 2008). Our multi-epoch observations also detect variability of the absorption-line energies and equivalent widths; the full rest-frame energy range over which absorption has now been seen is 7.5–17 keV. Such variability is expected given the likely small launching radius of the outflow, and it also helps to explain the somewhat different initial interpretations of the absorption features put forward by Chartas et al. (2002) vs. Hasinger, Schartel, & Komossa (2002).

After our first report of iron K BALs from APM 08279+5255, several additional examples of possible relativistic outflows from luminous quasars were reported (e.g., Chartas, Brandt, & Gallagher 2003; Pounds et al. 2003; Gibson et al. 2005; Pounds & Reeves 2009; Reeves et al. 2009), some more convincing than others. Hopefully the number of luminous quasars with evidence for relativistic X-ray absorbing outflows will continue to grow, so that astronomers can build up a clearer picture of their kinetic luminosities and their apparently significant role in feedback.

**SOME FUTURE PROSPECTS**

The statistical X-ray studies of luminous quasar winds described above should advance rapidly over the coming decade, due to the combination of new large optical spectroscopic surveys of quasars and the continually growing X-ray archives. For example, the SDSS-III BOSS survey (e.g., Schlegel, White, & Eisenstein 2009) will obtain spectra for about 160,000 quasars at $z \approx 2–4$. These will generally have excellent coverage of tran-
sitions such as C IV, Si IV, and Al III, and more than 30,000 new BAL and mini-BAL quasars should be discovered. Hundreds of these will already have sensitive archival X-ray coverage from Chandra and XMM-Newton that may be used to define in detail correlations between X-ray absorption, UV absorption, luminosity, and other physical properties.

The X-ray Microcalorimeter Spectrometer (XMS) on the International X-ray Observatory (IXO) should dramatically advance studies of X-ray BALs in luminous quasars. The large (up to 2–3 m²) IXO collecting area will provide sufficient photon statistics for reliable X-ray BAL detections in 20–80 ks for many quasars. Equally important, the XMS spectral resolution (2.5 eV) will allow study of the detailed structure of X-ray BALs, which is likely complex given the known complexity of UV BALs. From these results, we expect substantial new insights into the energetics of quasar winds and their role in galaxy feedback.

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