AGN OUTFLOWS IN EMISSION AND ABSORPTION: THE SDSS PERSPECTIVE

GORDON T. RICHARDS 2

ABSTRACT

A variety of investigations have demonstrated commonalities between the Baldwin (1977) Effect, the blueshifting of C IV emission lines (e.g., Gaskell 1982; Richards et al. 2002), and the $L_{UV}-L_X$ relationship (e.g., Avni & Tananbaum 1982; Strateva et al. 2005; Steffen et al. 2006); indeed all three of these observational effects may be manifestations of the same underlying (but still uncertain) physics. This commonality is of interest to investigations of accretion disk winds (e.g., Murray et al. 1995; Proga et al. 2000) from active galactic nuclei (AGN) as there is evidence that broad absorption line quasars (BALQSOs) are drawn from a parent sample of quasars that exhibit larger than average C IV blueshifts, weaker than average C IV emission line strengths, and bluer than average (intrinsic) colors. The properties of the absorption troughs appear to be dependent upon these parameters. Thus, it is suggested that not all quasars will host bona-fide BAL troughs, but that all (broad emission line) quasars host outflows of some type, the structure of which is strongly dependent on the quasar’s spectral energy distribution.

1. INTRODUCTION/REVIEW OF RICHARDS ET AL. (2002)

While quasar spectra appear quite similar, there are a number of well-studied distinctions that provide a basis for quasar sub-classification. Two of those effects involve changes in the C IV emission line; these are the (Baldwin 1977) Effect (BEff) and the blueshifting of the peak of the C IV emission line with respect to the quasars’ systemic redshift (Gaskell 1982; Wilkes 1984). In the interim years, numerous papers have considered these phenomena, exploring their dependence on radio loudness, luminosity, the shape of the spectral energy distribution and the extent to which lines other than C IV are effected (e.g., Mushotzky & Ferland 1984; Kallman & Krolik 1986; Binette et al. 1989; Tytler & Fan 1992; Zheng & Malkan 1993; Brotheron et al. 1994; Marziani et al. 1996; Korista et al. 1998; Elvis 2000; Sulentic et al. 2000; Leighly & Moore 2004; Leighly 2004; Wilhite et al. 2006).

Recently, Richards et al. (2002, hereafter R02) investigated the blueshifting of C IV emission for a large sample (> 700 quasars) drawn from the Sloan Digital Sky Survey (SDSS; York et al. 2000). R02 confirmed previous results that showed that C IV blueshifts are ubiquitous in radio-quiet quasars and that radio-loud quasars tend towards smaller blueshifts; see also Marziani et al. (1996). It was also shown that quasars with large blueshifts have C IV emission lines that have larger FWHM, but smaller equivalent widths than the average quasar; see also Corbin (1990). R02 found that controlling for luminosity does not eliminate the effects of C IV blueshifts, but that large blueshift quasars are somewhat bluer and more luminous than quasars with small blueshifts.

An outflow such as from an accretion disk wind (e.g., Murray et al. 1995; Murray & Chiang 1997; Proga et al. 2000; Chelouche & Netzer 2003; Everett 2005) is often cited as the most plausible explanation for the origin of C IV blueshifts (e.g., Leighly 2001). While an outflow related origin for this effect seems likely, R02 pointed out that there is good agreement in the blue wing between blueshifted and un-blueshifted objects and argued that these blueshifts are not well explained by a simple translation of the line, but rather that the red wing is preferentially affected by absorption, suppression, and/or obscuration; see also Leighly (2001). It is important to consider this possibility as it would have strong negative implications for the use of the C IV emission line in black hole mass (and possibly metallicity) determinations.

Finally, R02 suggested that C IV blueshifts may represent an orientation effect. This could be in terms of an external orientation effect such as the tilt of the accretion disk with respect to our line of sight, or it could be an internal orientation effect such as the opening angle of the accretion disk (e.g., Elvis 2000, Fig. 7; Everett et al. 2001, Figs. 1 and 2). Current evidence would seem to favor the latter interpretation as radio-loud objects preferentially exhibit small blueshifts — regardless of their radio morphology (and thus orientation).

Finally, it is important to emphasize that the C IV blueshift effect is related to the results derived from eigenvector decomposition (Boroson & Green 1992; Brotheron & Francis 1999; Sulentic et al. 2000; Boroson 2002; Yip et al. 2004) and that it has been argued (e.g., Baskin & Laor 2005) that the C IV line profile is governed by $L/L_{Ed-d}$.

2. NEW/UPDATED BLUESHIFT RESULTS

With a much larger sample of quasars than the SDSS Early Data Release sample used by R02, it is now possible to explore trends that were not possible to explore before. Figure 1 shows the distribution of C IV blueshifts for over 7500 SDSS-DR4 (Adelman-McCarthy et al. 2006) quasars — nearly 10 times the sample size from R02. It is quite clear that these shifts of the C IV emission line with respect to Mg II are ubiquitous for the population as a whole, yet are much smaller for radio-loud quasars. R02 built composite spectra in 4 bins of C IV blueshift

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2 Department of Physics & Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218.
and showed that, on the average, quasars with large C IV blueshifts have bluer than average continua. Similarly, Richards et al. (2003) showed that bluer quasar tend to have weaker emission lines (particularly C IV). However, further work has found that there is not a simple one-to-one relationship between the continuum color and the emission line strength/blueshift (e.g., Gallagher et al. 2005). This can be seen in Figure 2 which shows that while quasars with large C IV blueshifts are generally blue, not all blue quasars have large C IV blueshifts. Thus it is necessary to reconsider the composite spectra properties investigated by R02 as a function of color in addition to blueshift. Figure 3 depicts the results of making composite spectra of quasars drawn from three extrema in Figure 2: blue quasars with large C IV blueshifts, blue quasars with small C IV blueshifts, and red quasars with small C IV blueshifts. The samples are designed to have roughly equal numbers in each category, with over 600 quasars in each bin. Red and blue quasars with small blueshifts have quite similar emission features (perhaps with the exception of Lyα). On the other hand, blue quasars with large and small blueshifts have drastically different emission line properties despite quite similar continua.

An obvious question is whether these differences are due to luminosity. R02 showed that, while quasars with large blueshifts are somewhat more luminous and bluer, controlling for luminosity effects (using $M_i$) did not mitigate the C IV blueshift effect. Nevertheless, it is still true that there exists a weak trend with luminosity, in a manner similar to the Baldwin Effect, see Figure 4.

R02 also investigated the blueshift distribution as a function of radio and X-ray brightness. It was found that radio-loud quasars had smaller blueshifts as is demonstrated in Figure 1. X-ray (ROSAT) detected objects, however, showed a more even distribution across all blueshifts, but with a slight tendency towards X-ray detections being associated with smaller blueshifts (particularly for pointed ROSAT observations). Here we have a large enough sample to extend this investigation. Using the (pipeline-measured) 2800 Å continuum flux density (at Mg II) and the ROSAT count rate we compute $\alpha_{ox}$, the ratio of flux densities at 2500Å and 2keV comparison (assuming $\alpha_{\nu} = -0.5$). As can be seen in Figure 5, X-ray strong quasars ($\alpha_{ox} > -1.45$) have smaller than average blueshifts — perhaps consistent with the X-ray strength of radio-loud quasars (Shastri et al. 1993). On the other hand, X-ray weak quasars tend towards larger blueshifts. However, as $\alpha_{ox}$ is correlated with $L_{UV}$ (Steffen et al. 2006, and references therein), it is difficult to determine whether this trend is due to the optical or X-ray.

Along these lines, it is interesting to note that using Chandra data for a dozen SDSS quasars representing the extrema in the C IV blueshift distribution, Gallagher et al. (2005) showed that large blueshift objects have somewhat steeper hard X-ray spectra than small blueshift quasars and that the large blueshift quasars appear to be absorbed in soft X-rays. This trend is consistent with our finding here that large blueshift quasars are more X-ray weak.

Thus, large C IV blueshift quasars may be more UV luminous than average, have bluer than average UV spectral indices, and have steeper than average hard X-ray spectra (that are either absorbed or intrinsically weak in soft X-rays). These are the very properties needed for effective radiation pressure driving of an accretion disk wind (e.g., Proga et al. 2000; Leighly 2004).

3. C IV blueshifts = the Baldwin Effect

It has long been realized that the $L_{UV}$–$L_X$ relationship and the BEff may not be independent (e.g., Zheng & Malkan 1993; Green 1998; Korista et al. 1998), particularly given that both relationships depend on the optical/UV luminosity and that the soft X-ray spectrum (47.9–64.5 eV) is responsible for the relative abundance of triply ionized carbon.

Here that argument is extended to include C IV blueshifts. That is, C IV blueshifts, the BEff, and the $L_{UV}$–$L_X$ relationship are suggested as having common origin; see also Leighly (2004). The arguments for this commonality are simple, yet powerful. Two primary lines of evidence suggest a unification of the BEff and the blueshunting of C IV emission lines. First, as with the BEff, there is a weak luminosity trend in the C IV blueshifts: quasars with large blueshifts are slightly more luminous, see the left hand panel of Figure 4. Second, quasars with large blueshifts have smaller C IV equivalent widths, see the left hand panel of Figure 6. Thus, $L_{UV}$, C IV equivalent width, and C IV blueshift appear to be correlated with each other. None of these trends are particularly tight — there is large scatter in the luminosity trends and any correlation between C IV blueshift and C IV EQW are largely due to a lack of large EQW lines in large blueshift objects; however, the trends do appear to be robust.

A connection between C IV blueshifts and the $L_{UV}$–$L_X$ relationship is supported on both an empirical and a theoretical basis. Empirically, we saw in Figure 5 that quasars that are stronger in the X-ray relative to the optical/UV ($\alpha_{ox}$ less negative) have smaller C IV blueshifts. Theoretically, it is perhaps not surprising that changes to the C IV emission line are seen with increasing UV luminosity (and thus $\alpha_{ox}$ less X-ray luminosity) given that the production of C IV is regulated by the incidence of X-ray photons.

Further supporting these connections is the similarity of the emission lines involved in each effect (and to what extent) and their ionization potential. For, example, He II 1640Å has a trend that is highly correlated with the C IV blueshift, and, as emphasized by Leighly & Moore (2004), weak He II may be indicative of a relative paucity of soft X-rays. Also, Si IV (which may have a strong contribution from O IV) shows a weak blueshift effect at best (see the insets in Figure 3). These trends are consistent with the general trends for the BEff (e.g., Dietrich et al. 2002).

Finally, while not all previous work agrees on this point, Francis & Koratkar (1995) showed that the Baldwin Effect is strongest in the red wing of the C IV emission line. This is equivalent to saying that C IV blueshifts and the BEff are the same phenomenon.

Thus, both the BEff and C IV blueshifts are seen under similar conditions, produce similar effects, and have the same dependence on the X-ray part of the spectrum, suggesting a commonality between these relationships. The equality of all three of these effects is not generally appreciated in part because the C IV emission line is often used to define a quasar’s systemic redshift (thus obscur-
ing the blueshift effect) and because it can be difficult to disentangle SED effects from luminosity effects (especially when using broad-band luminosities).

4. THE BALQSO PARENT SAMPLE

The above X-ray/blueshift relationship is particularly interesting when considering the claims by Corbin (1990), R02, and Reichard et al. (2003b) that BALQSOs have larger than average blueshifts. Furthermore, BALQSOs are known to exhibit strong X-ray absorption and very negative values of $\alpha_{ox}$ (e.g., Brandt et al. 2000; Gallagher et al. 2006). In Figure 7, we show how, despite absorption blueward of the peak of C IV emission, it is still possible to use the red wing of C IV, the He II emission line, and the C III] emission complex to demonstrate that BALQSOs have larger than average blueshifts (LoBALs exhibiting the largest blueshifts).

Reichard et al. (2003b) and Trump et al. (2006) further showed that, after correction for dust reddening, intrinsically red and intrinsically blue HiBALs have distinct emission and absorption properties. “Red” HiBALs have much stronger C IV, He II, and C III] emission lines than “blue” HiBALs — consistent with the emission line differences seen in non-BALQSOs by Richards et al. (2003) and in Figure 3 above. Further, blue HiBALs appear to exhibit BAL troughs that extend to higher maximum outflow velocities. These relationships are of great interest for disk-wind models, especially when considered in concert with the results of Gallagher et al. (2006, Fig. 5) showing that X-ray faint quasars have weaker C IV emission lines, and C IV absorption troughs that are broader and extend to higher velocities.

Thus, not only does it seem that quasars with certain SEDs (and emission line properties) are more likely to host BALQSOs, the SED determines what kind of BALQSO a quasar can host. Since the blueshift and color distributions appear continuous, we speculate that this SED dependence extends from BALQSOs (Weymann et al. 1991; Reichard et al. 2003a; Trump et al. 2006) to those with NALs (Foltz et al. 1986; Hamann et al. 1997; Richards 2001; Ganguly et al. 2001; Vestergaard 2003) and from radio-quiet to radio-loud objects (e.g., Stocke et al. 1992; Becker et al. 2000; Menou et al. 2001), perhaps as a result of a gradual transition from a radiation-dominated wind (Proga et al. 2000) to an MHD-dominated wind (Konigl & Kartje 1994; Everett 2005); see also Everett et al. (2001), Proga (2003) and Richards et al. (2004).

In this picture the 15% BALQSO fraction (e.g., Weymann et al. 1991; Tolea et al. 2002; Reichard et al. 2003b; Hewett & Foltz 2003; Trump et al. 2006) represents neither a separate class of objects nor the BAL covering fraction of a single population of objects. But rather it is likely that the BAL covering fraction is quite large for one extremum of the quasar population (blue, blueshifted quasars) and is essentially zero for the opposite extremum (though these objects likely still have outflows, it is just that they are not strong enough to be classified as bona-fide BALQSOs). In this case the 15% fraction is merely the SED-averaged BALQSO fraction.

We can summarize this graphically in Figure 8. Blue quasars with weak, blueshifted CIV (top panel) are the parent sample of BALQSOs. Along some lines of sight the top quasar will exhibit BAL troughs. Even bluer quasars with even weaker, more strongly blueshifted CIV such as the middle quasar are likely to show Low-ionization BAL troughs. Such an object may only be a HiBAL along some lines of sight (whereas the top quasar may not show low-ionization troughs along any lines of sight). Red quasars with strong CIV that is not blueshifted, such as the bottom quasar, have considerably different SEDs that result in significantly different wind structures, and along no lines of sight would the bottom quasar exhibit BAL troughs. However, such quasars likely still have a wind and may show intrinsic NAL absorption. Note also that the bottom quasar has a much greater than 10% chance of being radio-loud, while the top objects have little (if any) chance of being radio loud — the wind structure also being related to that aspect of quasar properties.

5. DISCUSSION/CONCLUSIONS

An obvious chicken and egg question underlies all of these results. Specifically, is there a single common quasar SED whose appearance is affected by material along our line of sight, or is there a range of intrinsic quasar SEDs that affect the structure of the disk wind, and thus the emission/absorption material that is seen along our line of sight? An argument against a common SED is that fact that radio-loud quasars do not span the full range of SEDs or spectral properties (e.g., emission/absorption line strength). Even among radio-quiet quasars the fact that the bluest quasars exhibit the greatest tendency for UV and X-ray absorption suggests a heterogeneous intrinsic SED distribution. Finally, it should be remembered that disk-wind models are highly dependent on the intrinsic UV to X-ray flux ratio (e.g., Proga & Kallman 2004; Proga 2005).

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Fig. 1.— Blueshift of the CIV emission line (with respect to MgII) for over 7500 SDSS-DR4 quasars (Adelman-McCarthy et al. 2006). Positive values indicate a blueshift of CIV (and thus erroneously small systemic redshift) with respect to MgII. Only non-BAL quasars with small errors (<300 km/s) in this quantity are shown. Radio-loud quasars ($\log L_{\text{rad}} > 33$ [ergs/s/Hz]) are shown in gray after scaling by a factor of 6 for comparison with the full sample. Dashed lines indicate the median values.
Fig. 2.— Blueshift of the CIV emission line versus relative $g - i$ colors, $\Delta(g - i)$. The relative color is computed by subtracting the mean $g - i$ color as a function of redshift from each observed value and is a robust indicator of optical spectral index that is independent of redshift and (average) emission line strength (Richards et al. 2003). R02 constructed composites in 4 bins of CIV blueshift, but it is clear that there are differences in optical color that should be accounted for. While quasars with large CIV blueshift are generally blue, not all blue quasars have large CIV blueshifts.
Fig. 3.— Composite spectra of blue, large blueshifted (blue); blue, small blueshifted (cyan); and red, small blueshifted (red) quasars. Each composite contains over 600 quasars. The main panels are normalized at 2200 Å, for comparison of the spectral slopes, while the insets have local normalizations so that the line profiles can be compared. Note that, with the exception of Lyα, the blue and red composites with small CIV blueshifts have very similar emission line features. Likely dust reddened quasars \( \Delta(g - i) > 0.2 \) have been excluded in all composites.

Fig. 4.— There are weak trends between UV luminosity \( L_{1550\text{Å}} \) and CIV blueshift and CIV equivalent width. The latter being the Baldwin (1977) Effect.
Fig. 5.— There is a weak tendency for quasars that are X-ray weak (relative to the UV/optical) to have larger blueshifts.
Fig. 6.— Quasars with large blueshifts have small equivalent widths and “broader” lines.
Fig. 7.— Comparison of HiBAL and LoBAL composites to CIV blueshift composites. Blueshift composite A (upper left hand panel) has the smallest CIV blueshifts, composite D (lower right hand panel) has the largest blueshifts. By comparison with the red wing of CIV and the CIII] emission line region, it is seen that BALQSOs have larger than average CIV blueshifts, LoBALs being more extreme than HiBALs. (Adapted from R02).
Fig. 8.— *Top:* Quasar without BAL absorption along our line of sight, but with spectral features (blue continuum, weak, blueshifted emission lines) indicating that it is likely a BALQSO along other lines of sight. *Middle:* A more extreme version of the top object, possibly possessing a strong enough radiation driven wind to produce a low-ionization BAL troughs along some lines of sight. *Bottom:* A quasar with a relatively red continuum and strong CIV emission that is not blueshifted with respect to MgII. Such a quasar is unlikely to exhibit BAL troughs along *any* line of sight, though it may still exhibit weaker outflow features. In each panel, the emission line peaks are marked by dashed lines according to the redshift derived from the MgII emission line.