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Toward an Understanding of the Baldwin Effect: is the Eddington Ratio the Key Factor?

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Abstract. We present composite UV spectra for low redshift type 1 AGN binned in the context of the Eigenvector 1 (E1) parameter space. Median spectra for the 1000-3000 Å spectral range were computed following the spectral types defined in Sulentic et al. (2002) for the Hβ spectral region. The composites show high enough S/N and spectral resolution to permit a proper measurement of the C IVλ1549 line – one of the strongest high-ionization lines and one of the most frequently used to define the Baldwin effect. We find a ten-fold decrease in equivalent width of the C IVλ1549 line while the Eddington ratio increases from ≈ 0.01 to ≈ 1. At the same time there is no indication of equivalent width change for the N Vλ1240 line. These trends describe a luminosity-independent "Baldwin effect," and suggest that a physical driver of the long-debated Baldwin effect may be the Eddington ratio.

Key words. quasars: emission lines – galaxies: active – cosmology

1. Introduction

The original "Baldwin effect" (BE) was established as a tight anti-correlation between C IVλ1549 and continuum luminosity using a few tens of objects (Baldwin 1977). More recent work (Croom et al. 2002; Dietrich et al. 2002; Warner et al. 2003) has re-defined the BE as a very loose correlation that becomes significant only over a very wide range in continuum luminosity $\log(\lambda L_\lambda) \sim 42$–48 ergs s^{-1} (as in Kinney et al. 1990). Considering the large dispersion it is not surprising that several studies using small samples found no evidence for a BE (see Sulentic et al. (2000) for numerical simulations and a thorough discussion of the issue). A recently-appreciated, complicating factor involves low-luminosity sources that have low W(C IVλ1549), $\sim$ 10-30 Å since they tend to blur even more the Baldwin relationship. These Narrow Line Seyfert 1 (NLSy1) sources preferentially occupy the lower left part of a $\log W$ vs. $\log L$ diagram.

2. The Eigenvector 1 Sequence, Spectral Type Definition & the UV Data

The optical and UV spectra of luminous Seyfert 1 and low redshift quasars are not all

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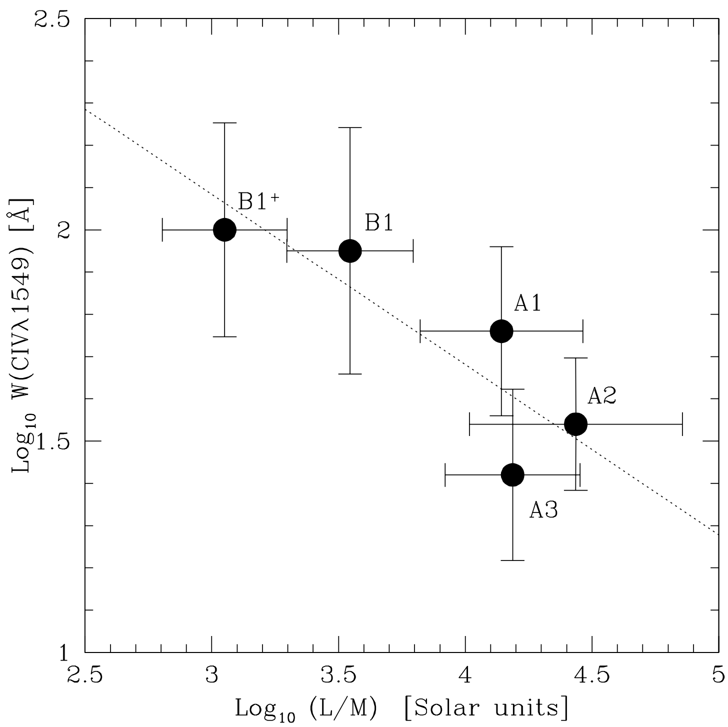

Fig. 1. Median equivalent width of the C IV λ1549 line as a function of the luminosity to mass ratio L/M, in solar units. The five points refer to the spectral types defined by Sulentic et al. (2002). Error bars are sample standard deviations. The thin line is a formal best-fitting solution (see §3 for details).

look-alikes. The diversity and correlation of broad line AGNs are clearly shown by their distribution in the so-called "Eigenvector 1 (E1) optical plane," defined by the FWHM of the Hβ broad component, FWHM(Hβ), vs. the equivalent width ratio between the Fe II blended emission at λ4570, and Hβ broad component, $R_{\rm Fe}$ = W(Fe II λ4570)/W(Hβ) (Boroson & Green 1992; Sulentic et al. 2000). Data points drawn from a sample of more than 200 broad-line AGN observed at moderate resolution (R≈1000 at Hβ) and mean S/N ≈ 30 allow the definition of typical spectral types covering a narrow range in FWHM(Hβ) and $R_{\rm Fe}$ (Sulentic et al. 2002). We set $\Delta R_{\rm Fe}$ = 0.5, and, for FWHM(Hβ)$\lesssim$ 4000 km s^{-1}, we define spectral type A1, A2, A3 in order of increasing $R_{\rm Fe}$. If FWHM(Hβ)$\gtrsim$ 4000 km s^{-1}, we define a second sequence of increasing FWHM(Hβ): B1, with 4000 $\lesssim$ FWHM(Hβ) $\lesssim$ 8000 km s^{-1}; B1$^+$, with 8000 $\lesssim$ FWHM(Hβ)$\lesssim$ 12000 km s^{-1}, and so on, keeping the condition $R_{\rm Fe} \lesssim 0.5$. Sources with FWHM(Hβ) $\gtrsim$ 4000 km s^{-1} and $R_{\rm Fe} \gtrsim 0.5$ are very rarely observed at low z.

A notable limit is at FWHM(Hβ) ≈ 4000 km s^{-1}. It separates Population A and B (see section on BLR below; Sulentic et al. 2000). Many properties of Population A and Population B sources - several of them related to structural differences in the Broad Line Region (BLR) – correlate with the first Eigenvector identified by Boroson & Green (1992).

Composite UV spectra covering C IV λ1549 were obtained from a total of about 700 reasonable quality (S/N > 3-4) HST spectra for 141 different AGN (quasars or bright Seyfert 1s; 61 are radio-loud) extracted from the Hubble archive. The majority of the spectra (83%) were obtained with the FOS camera and the rest with STIS.

3. An L/M Dependent Baldwin Effect

The sequence in the E1 optical plane is largely independent on luminosity. The main governing factor seems to be the Eddington ratio, that goes from $\approx$ 0.02 for B1 sources to $\approx$ 1 for the most extreme NLSy1 sources in bin A3 (Marziani et al. 2001; Sulentic et al. 2002). Orientation and black hole mass act as sources of scatter (Zamanov & Marziani 2002). Our analysis of equivalent width measures as a function of spectral bin reveals the following trends:

- Lines like Lyα, CIVλ1549, MgIIλ2800, OVIλ1034 show an EW decrease proceeding from B1$^+$ to A3 by factors of 2–4.
- The NVλ1240 line does not show any appreciable trend: W(NV)$\approx$ 20-25 Å in all spectral types.

These results essentially describe the properties of the so-called "Baldwin effect." In other words, the amplitude of the Baldwin effect (minimum W(CIV) $\approx$ 20 Å and maximum $\approx$ 200 Å) is well reproduced by sources spanning the range 0.02 – 1 in $L/L_{\rm Edd}$. Figure 1 shows W(CIV) versus the median luminosity-to-mass ratio for each spectral type defined from our sample ($L/M \propto L/L_{\rm Edd}$; $L/L_{\rm Edd} \approx 1$ corresponds to $\log L/M \approx$4.53 in solar units). A weighted (over sample variance) least-square fit yields log W(CIVλ1549) $\approx$ 3.29 – $0.40 \log(L/L_{\rm Edd})$. A highly-significant correlation (which will be shown elsewhere) with similar slope is obtained if all sources are considered as individual data points (cf. Baskin & Laor 2004). The slight displacement of spectral type A2 with respect to A3 (expected to show highest L/M) may primarily depend on small numbers; if all A3 sources in Marziani et al. (2003) are considered, the positions of A2 and A3 are consistent with expectations. We note in passing that results change if radio-loud and radio-quiet sources are analyzed separately (as recommended by Sulentic et al. 2000). Radio-loud sources (which are present especially in spectral types B1$^+$, B1 and A1) seem to follow a much shallower BE.

Highest $L/L_{\rm Edd}$ sources show the lowest W(CIVλ1549). Indeed, it is a well-established fact that NLSy1s show the lowest W(CIVλ1549) (Marziani et al. 1996; Rodriguez-Pascual et al. 1997) and that they are likely to radiate close to (or perhaps even above) the Eddington limit. Many known NLSy1 sources are relatively low redshift/luminosity sources. They tend to blur standard BE correlation at the low luminosity end because they have W(CIVλ1549) similar to the high redshift quasars. Sulentic et al. (2000) conjectured that the BE was caused by preferential (probably driven by selection effects and intrinsic evolution) detection of large $L/L_{\rm Edd}$ sources at high redshift (and hence high L).

4. Broad Line Region Structure & Baldwin Effect

A proper analysis of the CIVλ1549 line profile can yield deep insight into the BLR structure. There is an obvious dependence on the spectral type as far as the CIVλ1549 profile is concerned: large blueshifts are preferentially associated to low W(CIVλ1549), and to sources in the A bins (Population A; FWHM(Hβ) $\lesssim$ 4000 km s^{-1}). Such sources are the ones radiating at large $L/L_{\rm Edd}$, and showing the evidence of a decoupling between low- and high ionization emitting regions. Probably Population A sources are the only ones able to maintain a strong high-ionization outflow due to the high $L/L_{\rm Edd}$. They may be thought as relatively young or rejuvenated AGN, whose frequency may be strongly increasing with redshift z.

5. What about NVλ1240?

A circumstantial element supporting a role for the relative accretion rate $L/L_{\rm Edd}$ in the BE involves the constancy of W(NVλ1240) and the increasing intensity ratio NVλ1240/Lyα along the sequence from B1$^+$ to A3. The large values of W(NVλ1240) for all spectral types are suggestive of supersolar metallicity (Bentz &

Osmer 2004). In the case of A3 sources however, where the largest N vλ1240/Lyα equivalent width ratio is observed, metallicity should be ∼10 $Z/Z_{\odot}$, not far from the nitrogen-loud quasar 0553+338 (Baldwin et al. 2003). It is not unreasonable to suppose that nitrogen may have been enhanced by vigorous formation of massive stars that burn hydrogen via the CNO cycle in the AGN circumnuclear regions. The largest enrichment may have occurred in relatively young or rejuvenated quasars (possibly interacting and with surrounding Starbursts) radiating at large accretion rates as NLSy1s are thought to be (several NLSy1s hosts may be merging dwarf galaxies; Krongold et al. 2001), and as low W(C ivλ1549) sources may be in general.

6. Conclusion

Interpretation of the Baldwin Effect has been highly controversial with suggestions encompassing orientation effects, selection effects, black hole mass, etc. Given a complete (in terms of $L/L_{\rm Edd}$) sample, if our interpretation is correct, the BE may survive or disappear depending on the relative importance of evolutionary and selection effects. Deeper surveys may detect larger W(C ivλ1549) sources at high redshift. For instance, the distribution of W(C ivλ1549) at z$\gtrsim$4 in Constantin et al. (2002) intriguingly implies the existence of several sources with W(C ivλ1549)$\gtrsim$ 50 Å at log $L \sim 46.5$ ergs s^{-1}.

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