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KINEMATIC LINKAGE BETWEEN THE BROAD- AND NARROW-LINE–EMITTING GAS IN ACTIVE GALACTIC NUCLEI[1]

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ABSTRACT

We investigate the radial velocity difference between the [O III] λλ4959, 5007 and Hβ lines for a sample of ≈200 low-redshift active galactic nuclei. We identify seven objects showing an [O III] λ5007 blueshift relative to Hβ with an amplitude larger than 250 km s^{-1} ("blue outliers"). These line shifts are found in sources where the broad high-ionization lines (e.g., C IV λ1549) also show a large systematic blueshift. Such blueshifts occur only in the population A region of the Eigenvector 1 parameter domain (that also contains narrow-line Seyfert 1 galaxies). We suggest that [O III] λλ4959, 5007 blueshifts are also associated with the high-ionization outflow originating in these highly accreting sources. This is a direct kinematic linkage between narrow- and broad-line–emitting gas.

Subject headings: galaxies: active — quasars: emission lines — quasars: general

1. INTRODUCTION

Forbidden [O III] λλ4959, 5007 emission arises in the narrow-line region of active galactic nuclei (AGNs). This emission has now been partly resolved in the nearest AGN, where the geometry of the line-emitting gas has been found to be far from spherically symmetric. This suggests that measures of integrated [O III] λλ4959, 5007 emission may correlate with source orientation to the line of sight (Hes, Barthel, & Fosbury 1993; Sulentic, Marziani, & Dultzin-Hacyan 2000a and references therein). Observations and theoretical models (e.g., Steffen et al. 1997; Sulentic & Marziani 1999; Moiseev et al. 2001) both suggest a complex interplay between (where applicable) shocks driven by radio ejection and the ionizing continuum from the nucleus.

At the same time, it is generally believed that radial velocity measures of the narrow emission lines (e.g., narrow Hβ and [O III] λλ4959, 5007) provide a reliable measure of the systemic, or rest-frame, velocity. [O III] lines are preferred because they are superposed on a much stronger broad-line component. Limited H I, CO, and absorption-line measures of the host galaxy rest frame suggest that [O III] λλ4959, 5007 usually gives consistent results within 200 km s^{-1} (de Robertis 1985; Whittle 1985; Wilson & Heckman 1985; Condon, Hutchings, & Gower 1985; Stirpe 1990; Alloin et al. 1992; Evans et al. 2001). Several observations, however, indicate that the narrow-line Seyfert 1 (NLSy1) galaxy prototype I Zw 1 shows an [O III] λλ4959, 5007 blueshift of $\Delta v_r = -500$ km s^{-1} relative to other rest-frame measures (Boroson & Oke 1987). This corresponds to a 10 Å shift, which is larger than any conceivable measurement or calibration errors (see Marziani et al. 1996).

We report here a study of the velocity shift of [O III] λ5007 relative to Hβ. Our aim was to identify objects with large radial velocity disagreement between [O III] λ5007 and Hβ and their relationship with the general population of AGNs.

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2. SAMPLE AND DATA ANALYSIS

We measured the (narrow line) velocity difference between the peak of [O III] λ5007 and of Hβ using our database of spectra for $n = 216$ AGNs. The data set includes CCD spectra obtained over the past ≈10 yr for studies of the Hβ region in Seyfert 1 galaxies and low-redshift ($z \lesssim 0.8$) quasars. Spectra were obtained with the following telescopes and spectrographs: ESO 1.5 m (Boller & Chivens [B&Ch]), San Pedro Martir 2.2 m (B&Ch), Calar Alto 2.2 m (B&Ch), Kitt Peak National Observatory 2.2 m (Gold), and Asiago 1.82 m (B&Ch). Results based on these spectra can be found in Marziani et al. (1996) and Sulentic et al. (2000a, 2002). The unpublished part of this data set will appear in a forthcoming paper (P. Marziani et al. 2002, in preparation). Spectra were taken with very similar instrumental setups yielding resolution in the range 4–7 Å FWHM. The signal-to-noise ratio (S/N) of our spectra is typically in the range ≈20–40 (minimum 12). The high S/N and the moderate resolution make this sample appropriate for the study of line shifts because FWHM and shift measures are not significantly affected by undersampling. Our AGN sample has an average source absolute B magnitude $\langle M_B \rangle \approx -23.7 \pm 2.0$ ($H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0$).

We deredshifted the spectra using an initial Hβ measurement for v_r in all sources where an Hβ narrow component could be identified. Optical Fe II_{opt} emission blends were then subtracted using the template method (Boroson & Green 1992). At this point, we measured v_r for Hβ a second time, as well as v_r for [O III] λ5007. Hereafter, we consider only the difference in radial velocities $\Delta v_r = v_r$([O III] λ5007) − v_r(Hβ) measured from the Fe II_{opt}–subtracted spectra. The measurement of Δv_r turned out to be possible for 187 sources. The 23 excluded sources include seven with no detectable [O III] λλ4959, 5007 emission and 16 with a very poorly defined Hβ line peak.

3. RESULTS

3.1. [O III] λλ4959, 5007 *Line Shift Distribution*

The distribution of Δv_r measures is shown in Figure 1*a*. The values range from −950 to +280 km s^{-1} with an average of $\langle \Delta v_r \rangle = -30$ km s^{-1}. The sample standard deviation is ±135 km s^{-1}. The median value is $\overline{\Delta v_r} = -7$ km s^{-1}; 50% of the measurements fall in the interval from −49 to +16 km s^{-1},

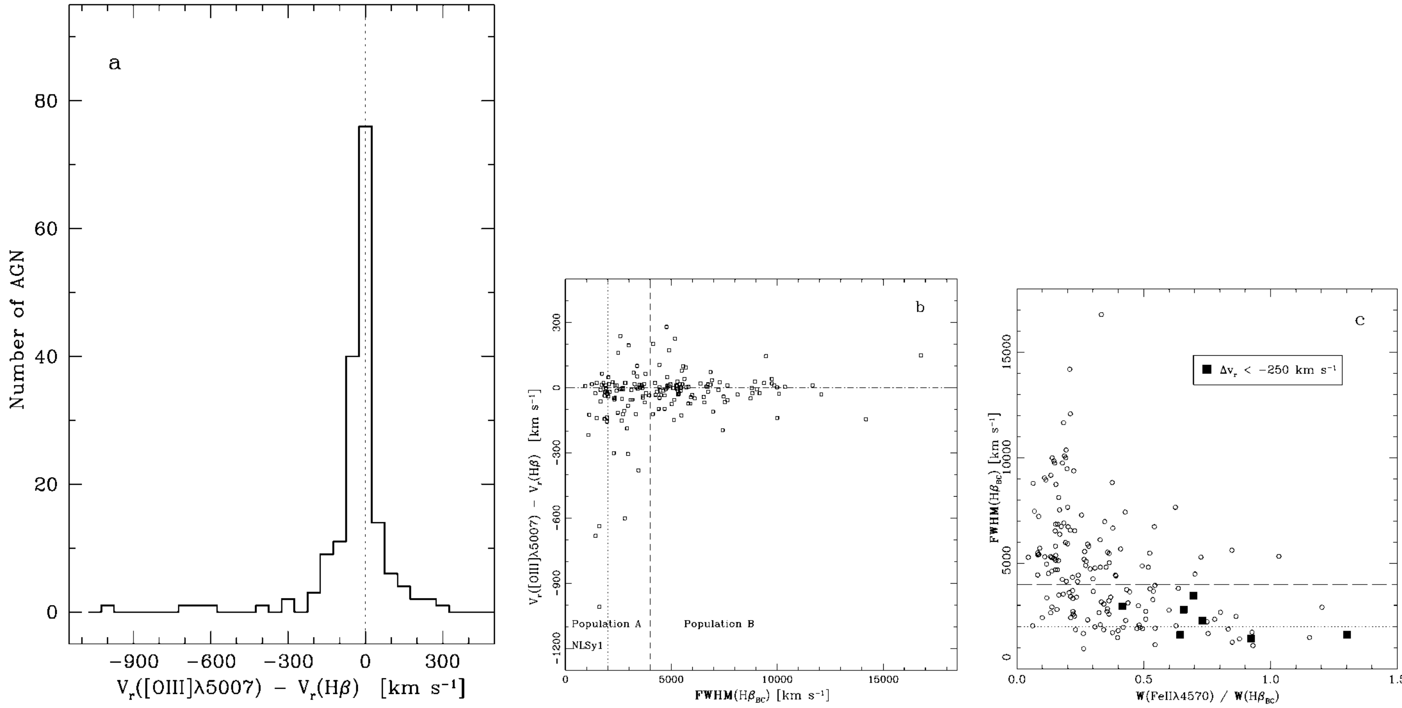

FIG. 1.—(*a*) Histogram showing the distribution of the radial velocity difference between the [O III] λ5007 and Hβ lines. (*b*) Radial velocity difference between the [O III] λ5007 and Hβ vs. FWHM(Hβ_{BC}). Vertical dotted line marks the boundary of the NLSy1 galaxies. Vertical dashed line separates population A and B sources. Seven objects with $\Delta v_r < -250$ km s^{-1} are visible. (*c*) Location of outliers in the FWHM(Hβ_{BC}) vs. $R_{Fe\,II}$ diagram (the optical E1 diagram). Filled squares represent the blue outliers ($\Delta v_r < -250$ km s^{-1}).

so we adopt the first and third quartile as confidence limits, $\overline{\Delta v_r} = -7^{+23}_{-42}$ km s^{-1}. The central bins of our Δv_r distribution are dominated by measurement errors, with typical values estimated to be in the range from 40 to 50 km s^{-1} at 1 σ confidence level. The continuous distribution of measures in the range -200 km s$^{-1} \lesssim \Delta v_r \lesssim +200$ km s^{-1} suggests that the [O III] λ5007 redshift measurements are consistent with Hβ to within the above range in more than 90% of the sources. The distribution of shifts is not symmetric around $v_r = 0$ km s^{-1} but is skewed toward the blue. Shifts in the range -200 km s$^{-1} \lesssim \Delta v_r \lesssim -100$ km s^{-1} are 3 times more frequent than redshifts in the range 100 km s$^{-1} \lesssim \Delta v_r \lesssim 200$ km s^{-1}. The maximum shift to the red is $\Delta v_r \approx 280$ km s^{-1}, while shifts up to $\Delta v_r \approx -1000$ km s^{-1} are observed on the blue side. The shift distribution reveals seven sources with [O III] λλ4959, 5007 shift ($\Delta v_r \lesssim -250$ km s^{-1}), which are listed in Table 1.

The relatively rare outliers (referred to hereafter as "blue outliers") are not randomly distributed in an Eigenvector 1 (E1; see § 3.3; Sulentic et al. 2000b) space representation of AGN diversity. Figure 1*b* plots [O III] λ5007 shift amplitude Δv_r versus the FWHM of the Hβ broad component [FWHM(Hβ_{BC})], and Figure 1*c* identifies the blue outlier sources in the E1 optical plane. Figures 1*b* and 1*c* suggest that large [O III] λ5007 blueshifts ($\Delta v_r \lesssim -300$ km s^{-1}) are confined to sources with FWHM(Hβ_{BC}) $\lesssim 4000$ km s^{-1}. The largest negative values ($\Delta v_r \lesssim -600$ km s^{-1}) are found at FWHM(Hβ_{BC}) $\lesssim 2000$ km s^{-1}. One radio-loud outlier PKS 0736 (-433 km s^{-1} blueshift) is found. It shows the largest FWHM(Hβ_{BC}) for any of the seven identified extreme blue outliers. Figure 2 presents Fe II–subtracted spectra of the region of Hβ and [O III] λλ4959, 5007 region for the seven blue outlier sources. They also show preferentially blue Balmer line asymmetries as was previously noted for NLSy1 galaxy sources.

3.2. *Are the Outliers Real?*

Even though the [O III] λλ4959, 5007 emission in these sources is weak, it is difficult to doubt the detection of such

TABLE 1

OBJECTS WITH ANOMALOUS DIFFERENCE OF THE RADIAL VELOCITIES BETWEEN THE [O III] λ5007 AND Hβ (BLUE OUTLIERS)

Name	z(Hβ)	Δv_r (km s^{-1})	W[O III] λ4959 (Å)	W[O III] λ5007 (Å)	$R_{Fe\,II}$	FWHM(Hβ_{BC}) (km s^{-1})	Δv_r(C IV λ1549$_{BC}$) (km s^{-1})
I Zw 1	0.0606	−640 ± 30	4.3	15.3	1.30	1600	−820
PKS 0736+01	0.1909	−430 ± 60	0.6	2.6	0.70	3460	…[a]
PG 0804+761	0.1014	−305 ± 30	3.3	10.1	0.42	2960	…[a]
Ton 28	0.3297	−680 ± 50	1.6	3.4	0.71	1860	−1120
PG 1402+261	0.1651	−300 ± 50	1.4	2.6	0.73	2280	−650
PG 1415+452	0.1151	−600 ± 50	1.1	2.9	0.66	2810	−950
PG 1543+489	0.4009	−950 ± 50	2.3	6.5	0.64	1600	−2630

NOTE.—Typical errors are ±30% in W[O III] λ4959, ±10% in W[O III] λ5007, ±0.15 in $R_{Fe\,II}$, ±150 km s^{-1} in FWHM(Hβ), and ±200 km s^{-1} in Δv_r(C IV λ1549$_{BC}$).

[a] *Hubble Space Telescope*/Faint Object Spectrograph observations not available.

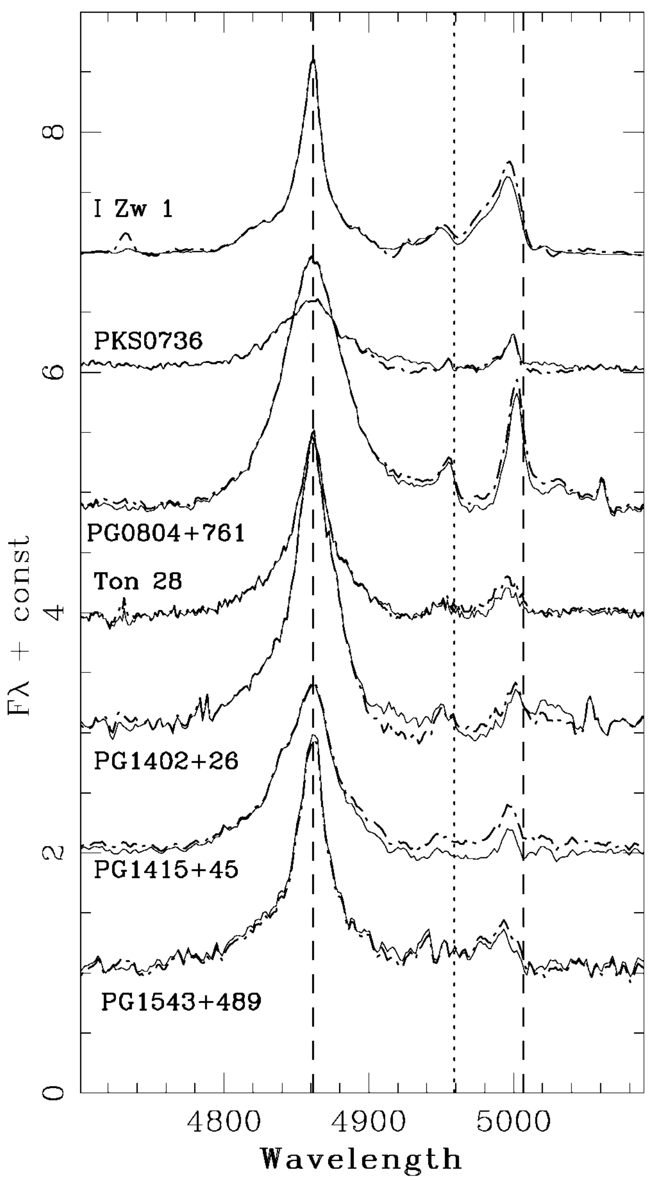

FIG. 2.—Hβ spectral region of the blue outliers after the deredshift and subtraction of the Fe II template. Spectra are normalized with respect to the local continuum and the arbitrary constant added. Solid curves correspond to the subtraction of an I Zw 1–based empirical template, and dot-dashed curves to the subtraction of a theoretical template. Vertical lines indicate the position of Hβ, [O III] λ4959, and [O III] λ5007. The difference in radial velocities between the [O III] λ5007 lines and Hβ is obvious.

large displacements in *both* [O III] λ4959 and [O III] λ5007 relative to the reference frame defined by Hβ (Fig. 2). We are able to measure the radial velocity of both [O III] λ5007 and [O III] λ4959, including those with low equivalent width. The velocities are always consistent within 100 km s^{-1}, and the equivalent width ratio of [O III] λ5007 and [O III] λ4959 is about 3 : 1 for the blue outliers, as expected (see Table 1). This and the fact that the shifts as well as the equivalent widths are different from source to source indicates that the [O III] $\lambda\lambda$4959, 5007 lines, although weak, are not strongly affected by the Fe II_{opt} subtraction. We further verified this with subtraction of a theoretical template in the region 4800–5100 Å (Sigut & Pradhan 2002), and the results, shown in Figure 2, are very similar.

One of the seven blue outliers (I Zw 1) has reliable independent host galaxy redshift determinations based on H I 21 cm and molecular CO observations (see, e.g., Schöniger & Sofue 1994). This is likely to be an accurate and reliable rest-frame determination for at least three reasons: (1) the H I and CO lines profiles match very closely in shape, width, and centroid velocity; (2) the profiles are symmetric; and (3) the profiles are steep-sided double horns. The centroid measures are consistent with the velocity of the peak of the Hβ emission-line profile and not with [O III].

Sources with FWHM(Hβ_{BC}) $\lesssim$ 4000 km s^{-1} show a sharply peaked, Lorentzian Hβ profile. In such cases the narrow-line component is uncertain because no profile inflection is seen. Even if the Hβ profile is completely ascribed to the broad component, it seems that the Hβ peak is nonetheless a good estimator of the quasar systemic velocity (this result is expected if the line comes from an extended accretion disk). We might expect to detect a *blueshifted* Hβ_{NC} analog to the [O III] lines, but given the low equivalent width W([O III] λ5007)—we normally expect W([O III] λ5007)/W(Hβ_{NC}) $\sim$ 10—such a blueshifted component will be lost in the noise.

We also attempted to identify red outliers (there are seven objects with $\Delta v_r \gtrsim 150$ km s^{-1}, which form an extended red tail in the shift distribution). In all cases, we find that the peak of Hβ is complex or even multipeaked. This means that the use of Hβ as a reference is sometimes ambiguous. Independent rest-frame measures for two of these sources are consistent with a radial velocity derived from [O III]. We therefore interpret Figure 1*a* as consistent with three populations: (1) a scatter population associated with measurement errors; (2) a real, but relatively rare, population of sources where [O III] λ5007 shows a large intrinsic blueshift relative to the local rest frame (the blue outliers); and (3) an intermediate population, in the range -250 km $s^{-1} \lesssim \Delta v_r \lesssim -100$ km s^{-1}, probably containing both sources with intrinsic blueshifts and sources with larger v_r(Hβ) uncertainty.

3.3. *Blue Outliers and Eigenvector 1*

Further insight and confidence about the reality of blue outliers can be gained from considering the distribution in the E1 diagrams (Sulentic et al. 2000b). The principal physical driver of E1 is assumed to be the luminosity-to-mass (L/M) ratio (proportional to accretion rate) convolved with source orientation (Marziani et al. 2001) and/or the black hole mass (Boroson 2002; Zamanov & Marziani 2002). The distribution of blue outliers in the E1 optical plane (Fig. 1*c*) is obviously different from that of the general AGN population. The blue outliers occupy the lower right part of the diagram and are exclusively population A/NLSy1 galaxy [FWHM(Hβ_{BC}) $\lesssim$ 4000 km s^{-1}] sources. A two-dimensional Kolmogorov-Smirnov test (see, e.g., Fasano & Franceschini 1987) suggests that the parameter space occupation of the *blue* outliers is significantly different than the majority of AGNs at a confidence level of 0.990–0.999. The preferred location of the blue outliers in E1 motivated us to search for other [O III] blueshifts among samples of phenomenologically similar sources. Grupe et al. (2001) identify a blueshift of 570 km s^{-1} in RXJ 2217$-$59. Our quick look at other (Fe II corrected) spectra (Grupe et al. 1999) revealed at least three other sources with obvious blueshifts in the range from -300 to -500 km s^{-1} (RXJ 1036$-$35, RXJ 2340$-$53, and MS 2340$-$15).

Figure 3 in Sulentic et al. (2000a) involving C IV λ1549 centroid shift versus FWHM Hβ shows a striking similarity to Figure 1*b* of this Letter. There is a high-ionization line (HIL)

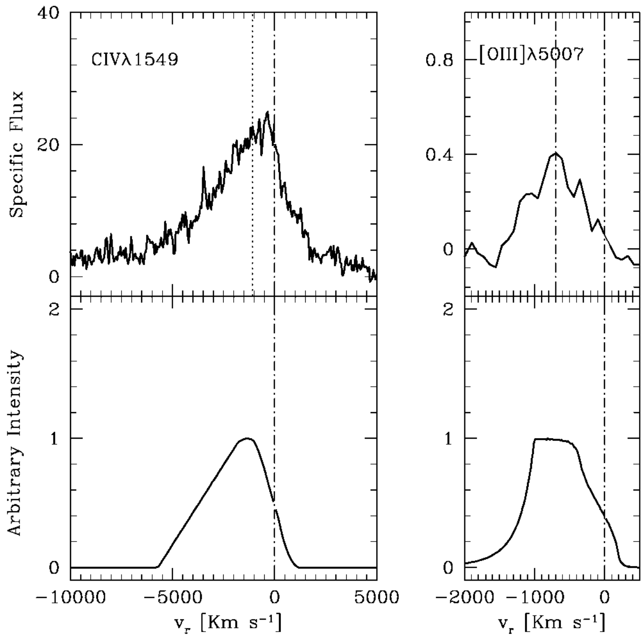

FIG. 3.—*Upper panels*: C IV λ1549 and [O III] λ5007 profiles of Ton 28, a blue outlier. *Lower panels*: C IV λ1549 and [O III] λ5007 outflow model profiles, for optically thin gas moving at approximately the local escape velocity. Profiles have been computed for a cone of half-opening angle 85°, with the line of sight oriented at 15° with respect to the cone axis. The receding part of the flow is assumed to be fully obscured by an optically thin disk.

blueshift in the same AGN (population A) where we find all of the blue outliers. The simplest interpretation is that we are seeing a kinematic linkage between broad-line region (BLR) and narrow-line region (NLR) HILs. A source-by-source comparison reveals five of seven blue outliers with *Hubble Space Telescope* Faint Object Spectrograph archival spectra of the C IV λ1549 line. The blue outliers show C IV blueshifts [at FWHM(C IV λ1549)] between $V = -503$ and -1936 km s^{-1}. This motivates us to look at all sources in our full sample with C IV shift (>600 km s^{-1}) and W[O III] (<15 Å) properties similar to the blue outliers. We find 12 additional sources where either (1) no narrow Hβ peak and/or [O III] line is observed (sometimes simply owing to noisier than average spectra); (2) smaller, likely significant, [O III] blueshifts are observed (e.g., -200 km s^{-1} for PG 1444+407); or (3) a peak + blue wing structure is observed. In the numerous latter cases we see a narrow, unshifted [O III] line with a strong blue wing. In the absence of the peak we would measure a blueshift in the blue outlier velocity range. This motivates us to propose that the blue outliers represent sources where the classical extended NLR is absent or suppressed. The peak + blue wing cases represent sources where both the (usually strong) classical and the (usually weak) blueshifted NLR components are present. The concept of two distinct NLR components is reinforced by sources such as NGC 7213 (Busko & Steiner 1988) and RXJ 0148−27 (Grupe et al. 1999), where both the unshifted and the blueshifted [O III] components are observed and resolved.

4. THE EXTREME OF AN EXTREME: LARGE SHIFTS GOVERNED BY ORIENTATION?

An obvious question involves whether or not the [O III] λ5007 blue outliers are peculiar AGNs—a new, previously unknown AGN class. They do not appear to be part of a continuous distribution of [O III] λ5007 velocity shifts. However, even if the distribution of [O III] λ5007 outliers is not consistent with the other AGNs in the E1 parameter plane, blue outliers lie near an extremum in the AGN-occupied domain rather than outside of it. If we consider our tentative grid of expected L/M and i values in the E1 plane (Marziani et al. 2001), we see that the blue outliers may be the product of special circumstances: (1) a large L/M ratio and (2) a small inclination ($i \rightarrow 0°$). Of course these two circumstances do not explain the absence of the classical NLR. One possibility is that (3) these sources are young quasars (see below). It has been suggested that NLSy1 galaxies are the radio-quiet equivalent of BL Lac objects. We infer that our blue outliers (the ones observed almost face-on, with largest C IV λ1549 and [O III] λ5007 blueshifts) may be the radio-quiet analogs of BL Lac objects. We note that the single radio-loud blue outlier identified PKS 0736+01 involves an optically violently variable quasar.

We constructed a purely kinematical model in which [O III] λλ4959, 5007 and C IV λ1549 are both assumed to arise in a radial flow constrained in a cone of half-opening angle $\Theta_0 \approx 85°$ (e.g., a high-ionization, optically thin wind), where the receding part of the flow is obscured by an optically thick accretion disk (i.e., we are able to see the approaching part of the flow and the near side of the disk assumed to emit Hβ). We assumed that radial motions in the gas were a fixed fraction (1.5) of the local virial velocity. We integrated over a region $100R_g \leq r \leq 10^5 R_g$ for C IV λ1549 and over a region $300R_g \leq r \leq 10^5 R_g$ for [O III] λ5007, with emissivity power-law indices $q = -2$ (C IV λ1549) and $q = -1$ ([O III] λ5007). Figure 3 shows the resulting model profiles for a viewing angle $i \approx 15°$. The width and shift of both lines can be accounted for. We suggest, without considering this particular model as a physical one, that emission from outflowing gas, possibly associated with a disk wind, can explain the observed profiles. The occurrence of large [O III] λ5007 shifts is associated with low W([O III] λ5007). Our model integration also consistently suggests *a very compact* NLR ($r \sim 1$ pc for a black hole mass of $10^8 M_\odot$). In this case, the receding part of the outflow may be more easily hidden by an optically thick disk extending to ~1 pc (this is also needed to avoid double-peaked profiles). The filling factor needed to explain the [O III] λ5007 luminosity of I Zw 1 and PG 1543+489 can be reasonably small, $\sim 10^{-3}$. It is intriguing that a compact NLR complements several lines of evidence suggesting that NLSy1 galaxies are young AGNs. Large W([O III] λ5007) would imply a larger emitting volume and hence may be associated with lower [O III] λ5007 shifts. The frequent observations of blueward asymmetry close to the [O III] λλ4959, 5007 line profile base indicates that the same outflow may be occurring also in the innermost NLR of AGNs with larger W([O III] λ5007).

It is also interesting to note that broad absorption line (BAL) quasi-stellar objects (QSOs) are found more frequently in samples with low W([O III] λλ4959, 5007) (Boroson & Meyers 1992; Turnshek et al. 1997). We do not find any BAL QSOs among the outliers. In addition, the known low-z BAL QSOs in our sample (PG 1004+13, PG 2112+059) with measurable [O III] λ5007 (two out of five) show shifts of $\Delta v_r \sim 0$ km s^{-1}. This is also consistent with orientation playing a role and with blue outliers being oriented predominantly face-on. On the contrary, the C IV λ1549 absorption/emission profiles of BAL QSOs suggest that they may be observed far from pole-on (P. Marziani et al. 2002, in preparation).

5. CONCLUSION

We find that the Hβ and [O III] λ5007 lines provide measures of the radial velocity of AGNs usually consistent within ± 200 km s^{-1}. We identified infrequent ($\approx$5% in a sample of 200 sources) AGNs showing $\Delta v_r \lesssim -250$ km s^{-1}. They belong to the extreme population A sources that also show a large broad-line C IV λ1549 blueshift. This kinematic coupling of the NLR and BLR HIL emission most likely involves a wind or outflow. Our analysis suggests that blue outliers are not peculiar objects, but rather AGNs of extreme L/M ratio with a compact NLR. A predominance of blueshifts in the sample indicates that [O III] λ5007 peak velocity is affected by outflow motions occurring in the innermost NLR.

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