THE BROAD LINE REGION OF QUASARS

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1. INTRODUCTION

“A thousand spectra are worth more than one average spectrum” is perhaps an appropriate modern extension of the aphorism “a spectrum is worth a thousand pictures” – at least for active galactic nuclei (Cox 2000; Dultzin-Hacyan et al. 2000). The “one thousand” spectra of a source are needed to obtain an estimate of the spatial extent of the broad line emitting region (BLR). The time delay between line and continuum flux variations (i.e. reverberation) is \( < 1 \) month, implying an angular size of just 0.1 arcsec at \( z \approx 0.010 \). Three orders of magnitude improvement in resolution is still needed to obtain a fuzzy view of the BLR with direct, space-borne optical imaging.

Monitoring several lines emitted by ionic species of widely different ionization levels would advance another, yet small step toward structure resolution. It is useful to separate lines into high ionization (HILs: \( \gtrsim 40 \) eV): CIV\( \lambda 1549, \) O IV\( \lambda 1400, \) He II\( \lambda 1640, \) He II\( \lambda 4686 \) and low ionization (LILs: \( \lesssim 20 \) eV): Balmer lines, Fe II, C II, Mg II\( \lambda 2800 \). A major effort in the 1990s established that HILs usually respond with shorter time-scales than LILs (see e.g., Korista et al. 1992 for NGC 5548). Unfortunately, studies of response in narrow radial velocity intervals across line profiles (i.e. 2D reverberation mapping) have slowed since then (but see Kollatschny 2003), not least because of technical difficulties demanding dedicated instrumentation (Horne et al. 2004).

Emission line properties of quasars do not scatter randomly with reasonable dispersion around an average, so that “one thousand” spectra are also needed to exploit spectral diversity as well as spectral variability. The range of observed H\( \beta \) FWHM spans more than one order of magnitude, from \( \approx 800 \) km s\(^{-1} \) to \( \approx 20000 \) km s\(^{-1} \) in some extreme sources. The Fe II prominence parameter \( R_{\text{FeII}} \) (defined as the intensity of the Fe II blend centered at 4570 \( \AA \) normalized by the intensity of H\( \beta \)) varies from almost 0 to \( \approx 1.5 – 2.0 \) in large quasar samples (Sulentic, Marziani & Dultzin-Hacyan 2000).

2. DIFFERENCES IN BLR STRUCTURE AND KINEMATICS

Considering the diversity of quasar properties, it seems meaningful to average spectra in bins defined within the so-called “Eigenvector 1 optical plane” of the 4D Eigenvector 1 parameter space (see J.W. Sulentic’ talk in these proceedings) or to separate at least narrower sources \( \text{FWHM}(\text{H} \beta_{\text{BC}}) \lesssim 4000 \) km s\(^{-1} \), Population A) and B (roader) sources. There is evidence in favor of two different BLR populations and of a meaningful limit at \( \text{FWHM}(\text{H} \beta_{\text{BC}}) \approx 4000 \) km s\(^{-1} \) (see Sulentic et al. 2007). The distinction between Population A and B may be more fundamental than either the RQ-RL or the NLSy1 vs. rest of quasars (BLSy1) dichotomies. Several tests find no significant distributional difference between NLSy1s
Fig. 1. HST/FOS (left panels) and optical, ground based spectra (right panels) of two representative sources: Mark 478 (Pop. A, top), and Fairall 9 (Pop. B, bottom). The strongest lines whose profiles are shown in the next figures are identified.

and sources with FWHM(HβBC) in the range 2000 – 4000 km s$^{-1}$, suggesting that the 2000 km s$^{-1}$ cutoff is artificial. Intriguing differences emerge if the Pop. A/B distinction is applied.

- Pop. A sources show Lorentzian HβBC profiles, most often symmetric or with slight blueward asymmetry, while Pop. B sources show double Gaussian HβBC profiles, often redward asymmetric (Sulentic et al. 2002, see also Fig. 1).

- The CIVλ1549 profile is most often blueward asymmetric and blueshifted in Pop. A, and it becomes a double Gaussian, redward asymmetric or symmetric in Pop. B. The CIVλ1549 and HβBC profiles appear to be more similar in Pop. B. (Sulentic et al. 2007, and references therein).

Figure 1 shows optical and UV spectra for typical pop. A and B sources. A visual impression is that the ionization degree is higher for Pop. B (Marziani et al. 2001), with lower $R_{\text{FeII}}$ and more prominent HILs. Kinematics and physical conditions may not be fully unrelated, for example if both Pop. A and B sources share a low-ionization region responsible for most or all of the Fe II emission, while a high-ionization, broader component is dominant in Pop. B only.

3. UV/OPTICAL SPECTROPHOTOMETRIC COMPARISON OF 2 PROTOTYPICAL SOURCES

We consider two sources in more detail, Mark 478 and Fairall 9, which are representative of Pop. A and Pop. B respectively (Fig. 1). HST/optical data allow us to analyze all the strongest emission lines from Lyα to Hβ.

Mark 478 (Fig. 2) – The HβBC profile is well fit by a Lorentzian function. If we assume that emission with the same profile is also present in CIVλ1549 then CIVλ1549 can be decomposed into this component and a rather strong, blueshifted component. A similar deconvolution very successfully reproduces the Lyα profile. No blueshifted component is detected in Hβ. Mg IIλ2800 is fit by a double Lorentzian.

Fairall 9 (Fig. 3) – HβBC and MgIIλ2800 are well fit with two Gaussian components, one narrower/unshifted and the other one much broader and shifted to the red (“very broad component”, VBC). Lyα and CIVλ1549 may be equally well-fit by two components. However, the VBC FWHM would be larger and the shift lower than in the case of Hβ and MgIIλ2800, suggesting the presence of a third component. We prefer to fit Lyα and CIVλ1549
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Fig. 2. Profile analysis results for Mark 478, the prototypical Pop. A source considered in this study. Ordinate is rest-frame specific flux in units of $10^{-15}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$, corrected because of Galactic extinction. Dashed lines indicate sum of line model emission, dotted lines indicate FeII emission. Due to the heavy FeII contamination we only fit the doublet core of MgII. See text for further details.

Fig. 3. Profile analysis results of Fairall 9 (Pop. B prototype). Units and meaning of symbols are the same of the previous Figure. Due to the non-simultaneity of the observations, and to the rather variable behavior of F 9 at the time the HST spectra were collected, it is not advisable to compare fluxes in the optical (H$\beta$) and UV lines. as shown in Fig. 3: a redshifted component analogous to the one identified in H$\beta$, and an additional blueshifted component.

A tentative nebular analysis can be carried out for the main components identified in the profile decomposition using CLOUDY photoionization computations [Ferland et al. 1998]. CLOUDY 7.0 incorporates a 287-levels model of the FeII ion following Verner et al. (1999). This is especially useful since we are able to measure the FeII emission for the 2000 – 3000 Å range (FeUV), at least normalized to Ly$\alpha$. We attempt to reproduce the observed line ratios for the main components identified in the two sources always assuming $N_H = 10^{23}$ cm$^{-2}$, standard AGN continuum, and solar abundances.

Mark 478: low ionization Lorentzian BC – A very low ionization component accounts for most emission in the H$\beta$ spectral region. Emission line ratios are best fit if ionization parameter is $\log \Gamma \lesssim -2$ and electron density $n_e \gtrsim 12$, where $n_e$ is expressed in cm$^{-3}$. High density and low ionization are especially needed to account for $R_{\text{FeII}} \approx 1$ and FeII$_{\text{UV}}$/Ly$\alpha \approx 1$. The very high $n_e$ is supported by the ratio CIII$\lambda$1176/Ly$\alpha \sim 0.1$.

Mark 478: blueshifted component – The blueshifted component in Mark 478 appears to be less well constrained, partly because it is very weak in the H$\beta$ range and strong in the UV lines. Ionization is presumably high for the gas emitting this component ($\log \Gamma \sim -0.5 \div -1.0$) and density may be $\log n_e \gtrsim 10 \div 11$ although $N_H$ may be substantially lower than assumed in our explorative calculations.

F 9: low ionization Gaussian BC – The lower ionization component, with narrower profile, is responsible for all of the FeII emission, which is not negligible in F 9: FeUV/Ly$\alpha \approx 0.4$, $R_{\text{FeII}} \approx 0.7$ for this component only (the 4DE1 $R_{\text{FeII}}$ includes all H$\beta$ flux [minus the narrow component] and is $\approx 0.4$). The observed ratios are best explained if $\log \Gamma \sim -2$, and $\log n_e \sim 11 \div 12$. These physical conditions are not much dissimilar from the ones deduced for the Lorentzian component of Mark 478 and, as expected, the CIII$\lambda$1176 line is detected.

F 9: high ionization, redshifted very broad Gaussian component (VBC) – The absence of “very broad” FeII emission, and the rather prominent “very broad” HeII 1640 suggest high ioniz-
tion. This broader component can be accounted for by ionization parameter \( \log \Gamma \sim -0.5 \sim -1.0 \), and moderate electron density \( \log n_e \sim 9.5 \sim 10.0 \). These parameters have been considered for a long time the canonical ones for the BLR.

**F 9: blueshifted component** – The high-ionization blueshifted component used to fit the Ly\(\alpha \) and C IV A1549 profiles (Fig. 3) is interpreted as analogous to the one observed in Mark 478.

Optical Fe II emission is self-similar in almost all sources within common S/N (~100) and \( \lambda/\Delta \lambda \sim 10^3 \) limits (Marziani et al. 2003a). The results obtained so far suggest that the similarity of the optical Fe II spectrum across Pop. A and B is due to emission through photoionization of a very dense medium. The connection between kinematics and ionization degree seems to be related to the relative prominence of the high and low ionization components in the HILs and LILs, since it is the low ionization component that produces all Fe II emission. How can we tentatively account for the different line profiles and different average ionization conditions in Pop. A and B sources?

4. PHYSICAL PARAMETERS BEHIND THE OBSERVED BROAD LINE DIVERSITY

4.1. Radio Loudness

First, we consider whether a powerful, radio jet somehow affects the observational properties of the BLR. To this aim, we compared median H\(\beta_{BC} \) profiles of 56 RQ and 36 RL sources in the black hole mass \( M_{BH} \) interval 8.5 < \( \log M_{BH} < 9.5 \) and unrestricted bolometric luminosity-to-mass \( L/M_{BH} \) ratio (Marziani et al. 2003b). Most of these will be Pop. B sources. The H\(\beta_{BC} \) profiles (after Fe II and narrow line subtraction) of RQ and RL sources are almost identical. The BLR (but not the Narrow Line Region!) does not seem to see whether a source is radio-loud or radio-quiet.

4.2. Luminosity

VLT/ISAAC data provide IR spectra with resolution and S/N similar to optical data. We observed 50 sources to cover redshifted H\(\beta \) (Sulentic et al. 2004, 2006). Luminous quasars in the range 1.0 \( \leq z \leq 2.5 \) still show Pop. A and Pop. B characteristics. LIL equivalent widths and \( R_{FeII} \) do not appear to depend significantly on \( L \), even on a \( \Delta m \sim 10 \) range. FWHM(H\(\beta_{BC} \)) is expected to increase \( \propto 10^{-0.083m_0} \) if broadening of H\(\beta_{BC} \) is due to virialized gas motions with \( r_{BLR} \propto L^{0.7} \) (see Sulentic et al. 2004 for details).

4.3. Gravitational Redshift

The centroid at 0 intensity \( c(0/4) \) of H\(\beta_{BC} \) loosely correlates with \( M_{BH} \); the correlation is significant \( (P \sim 10^{-3}) \) because such a large sample of \( \sim 300 \) sources has been considered. If gas motion remains virial down to the inner edge of the BLR there will be a simple relationship between the \( c(0/4) \) and FWZI. The amplitude of redward asymmetry depends on \( M_{BH} \) but gravitational redshift seems to be statistically inadequate to produce the \( c(0/4) \) redshifts. The difficulty is even more serious if the high-ionization VBC is considered alone.

4.4. Aspect Angle

The angle \( \theta \) between the line of sight and the radio jet axis can be estimated equalling the observed X-ray flux at 1 KeV to the flux expected from the synchrotron self-Compton process acting on radio photons to obtain the Doppler factor. The Lorentz factor can be then retrieved from the apparent velocity if the source is superluminal (following Sulentic et al. 2003 and references therein). Orientation matters, affecting the FWHM(H\(\beta_{BC} \)) by a factor \( \approx 2 \). This technique can be applied only to quasars with detected superluminal motion. There is yet no known way to retrieve individual \( \theta_s \) for the rest of AGN (Collin et al. 2006).

4.5. Eddington Ratio and Black Hole Mass

The H\(\beta_{BC} \) profiles change strongly as a function of Eddington ratio with profiles being generally Lorentzian if \( \log L/M_{BH} > 3.9 \) in solar units (Marziani et al. 2003b) and Gaussian or double-Gaussian below this limit. The mass \( M_{BH} \), estimated according to the virial assumption, yields second order effects, mainly in the line wings. The Eddington ratio also strongly affects high ionization lines like C IV A1549: significant and large blueshifts \( (\Delta v_t < -500 \text{ km s}^{-1}) \) are confined to Pop. A sources only (Sulentic et al. 2007). These results suggest that the Pop. A/B separation is physically motivated and driven by Eddington ratio.

4.6. Where is the Accretion Disk?

Few \( \approx 2\% \) in the SDSS), very broad sources, with FWHM \( \sim 6 \) times the average FWHM of Balmer lines (Strateva et al. 2003), show double-peaked profiles that suggest accretion disk emission. To adjust the theoretical to the observed profiles, non-axisymmetric or warped disks are most often required. A two component models for the LILs, a disk (corresponding to the high ionization component described in this paper) + a spherical one has
been successful for 12 AGNs, Pop. A and Pop. B. [Popović et al. 2004], but it is as yet unclear whether those results can be of general validity. Eddington ratios of double-peaked samples are much lower than those of typical type-1 AGN: \( \lesssim 0.02 \) in 90% [Wu & Liu 2004]. Old criticism based on line profile shape for the wide majority of AGN is still standing [Sulentic et al. 1990]: if only the accretion disk is emitting H\(_{\beta}\), we expect that at the line base the centroid shift is due to gravitational and transverse redshift, but this is not always the case, not even in Pop. B sources.

5. CONCLUDING REMARKS

Several BLR physical and kinematical properties seem to be governed primarily by the Eddington ratio. It was not so clear ten years ago. LILs properties are remarkably similar over a very wide range of luminosity, even at very high \( z \), and broad line profile shapes (both LILs and HILs) show only second-order effects that can be directly ascribed to \( M_{\text{BH}} \). We have also learned with more assurance that the BLR appears to be transparent to radio loudness. This does not mean that RL and RQ samples show similar spectra: only Pop. B RQ quasars and lobe dominated RL quasar show very similar spectra, with low Fe II emission and broad H\(_{\beta}\) [Marziani et al. 1996, Dultzin-Hacyan et al. 2000]. This may point toward a parallel evolution for RL and part of the RQ quasars: what makes them radio-different is an as yet unknown parameter that has little, if any, effect on their BLR.

We are still left with many conundrums concerning the actual origin of the BLR gas, its dynamics and spatial disposition. High-ionization gas (an accretion disk wind?), showing non-radial, outward motion and producing the blueshifted component observed in Mark 478 and, to a lesser extent, in F 9, may decrease in importance crossing the boundary from Pop. A, where it is strong in the HILs, to Pop. B where it may become almost hidden by the redshifted, very broad component. The central engine may sustain a most prominent outflow only if the Eddington ratio is relatively high, as in the case of Pop. A sources.

Placing these considerations on a firmer observational basis requires renewed efforts involving nebular diagnostics and line profile analysis, as well as the ability to understand how the viewing angle affects observed BLR parameters on a source-by-source basis, if we cannot count on 2D reverberation mapping. 4DE1 offers promise for decoupling source orientation from physics.

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