Constraining Quasar Structural Evolution with VLT/ISAAC

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We describe a VLT–ISAAC spectroscopic survey of the Hβ region for more than 50 quasars at redshifts between 1 and 3. We use the width of Hβ as a virial estimator of black hole mass and the Eddington ratio. The minimum observed width of Hβ increases from ~ 500–1000 km/s at low luminosity to ~ 3500 km/s in the high luminosity domain. This trend is consistent with the virial assumption and a broad line region size-luminosity relation with exponent α ~ 0.65. Broader lined sources show a second very broad and redshifted Hβ line component, which should be removed for reliable black hole mass estimation.

Forty-five years after their discovery we have a widely accepted idea about the nature of quasars, although much of a fundamental empirical understanding is still lacking. The standard paradigm sees all active galactic nuclei (AGN) as driven by gravitational accretion onto a supermassive black hole. This has led to the impression that all AGN are phenomenologically similar — a view reinforced by the low signal-to-noise (S/N) of most published source spectra. Future advances in understanding quasars will likely come from high S/N spectroscopic studies of broad emission line spectra because such measures provide the most direct clues about the kinematics and geometry of the central broad line region (BLR). They offer the only way to "resolve" the BLR in significant numbers of sources.

We reported in the June 2001 *Messenger* (Sulentic et al., 2001) on how spectroscopic observations with 1–3-metre-class telescopes were improving our understanding of quasar phenomenology through the development of a surrogate H–R diagram (now called 4-Dimensional Eigenvector 1 space: 4DE1) for these sources. The centrepiece of 4DE1 involves four parameters that emphasise correlations and differences between the quasar (defined as sources showing broad emission lines and optical Fe II emission) population (Sulentic et al., 2000ab; 2007). 4DE1 studies reveal a source dichotomy that we call Population A–B where the two populations distinguish: a) sources with "narrower" broad lines (FWHM Hβ = 500–4000 km/s) including Narrow Line Seyfert 1s (NLSy1), called Population A; and b) sources with broader lines (> 4000 km/s) including almost all radio-loud quasars, called Population B. We now report on a campaign of VLT–ISAAC spectroscopy (Sulentic et al., 2004; 2006; Marziani et al., 2009) for higher redshift quasars that enable us to extend our low-z results out to z ~ 2–3. Our VLT programme was designed to derive black hole masses using a single virial estimator (the full width at half maximum [FWHM] of the Hβ line). It was also designed to test the Population A–B concept that arose from our 4DE1 studies at low z.

Black hole masses (M_{BH}) and Eddington ratios (L/L_{Edd}) are fundamental parameters of interest to astrophysicists and cosmologists. The Eddington luminosity is that at which the gravitational force is balanced by radiation pressure. We think that M_{BH} and the Eddington ratio are also the principal drivers of source occupation in 4DE1 space, implying that Pop. A sources host the smallest M_{BH} (highest L/L_{Edd}) values and Pop. B the opposite (Marziani et al., 2003). But how are these key parameters measured — especially in high-z sources? The width of broad emission lines is considered a reliable indicator of velocity dispersion in the BLR gas surrounding the central black hole. FWHM Hβ is the measure of choice because the line is strong, relativelly symmetric and less uncontaminated by other lines. But how can we compare inferred properties of low-z quasars with higher redshift sources where Hβ cannot be observed in the optical domain? One solution was to use other low (Mg II 2798 Å) or higher ionisation (C IV 1549 Å) line measures. However it is more difficult to extract reliable FWHM measures for these lines due to strong Fe II contamination in the former case and because there is reason to doubt that the latter line is a valid virial estimator.

A more modern solution is twofold: 1) use low-z samples to obtain a better understanding (in the 4DE1 context) of source phenomenology; and 2) use VLT–ISAAC infrared spectroscopy to measure FWHM Hβ in high-z sources. The former involves estimating the effects of source orientation on line profiles as well as isolating the virial component of Hβ. M_{BH} determinations also require an estimate for the radius of the BLR (r_{BLR}) — only a small sample of low-z sources have reasonable estimates from reverberation mapping (Kaspi et al., 2005). We must therefore rely upon — and perhaps constrain — the correlation between r_{BLR} and source luminosity (i.e. the Kaspi relation).

Infrared observing strategy

There is a long history of infrared (IR) quasar spectroscopy (e.g., Kühr et al., 1984), but it has only recently become possible to obtain high S/N spectra of the Hβ region for significant numbers of high-z sources. ISAAC is the IR (1–5 μm) imager and spectrograph at the Nasmyth B focus of the VLT Unit Telescope 1 and high S/N spectra of z = 1–3 quasars can be obtained when Hβ is shifted into one of the IR "windows". Each spectrum corresponds to a wavelength range (IR windows Z, J, H, K) that covers all or, most often, part of the region involving Hβ, the Fe II 4570 Å blend and/or the Fe II 5130 Å blend. Accuracy in wavelength calibration is especially important and we obtain root mean square (rms) residuals of less than 20 km/s in all windows, which is comparable to the accuracy achieved for low redshift optical spectra with resolution $\lambda/\Delta\lambda$ ~ 1000.

VLT–ISAAC spectra collected in four observing seasons have enabled us to measure emission-line parameters for more than 50 quasars in the range $z = 0.9–3.2$. The sample size now permits a meaningful analysis of luminosity trends and source occupation in 4DE1 space. We chose ESO–Hamburg quasars (Wisotzki et al., 2000) as ISAAC targets, which ensured a well-defined colour-selected sample of sources brighter than $m_B = 17.5$. We used two large comparison samples of low-z quasars: 1) our atlas of 215 moderate S/N spectra (Marziani et al., 2003); and 2) the 450+ brightest quasars in SDSS (Zamfir et al., 2008). Figure 1 shows examples of both ground-based optical and VLT–ISAAC spectra over the full redshift range of our study.

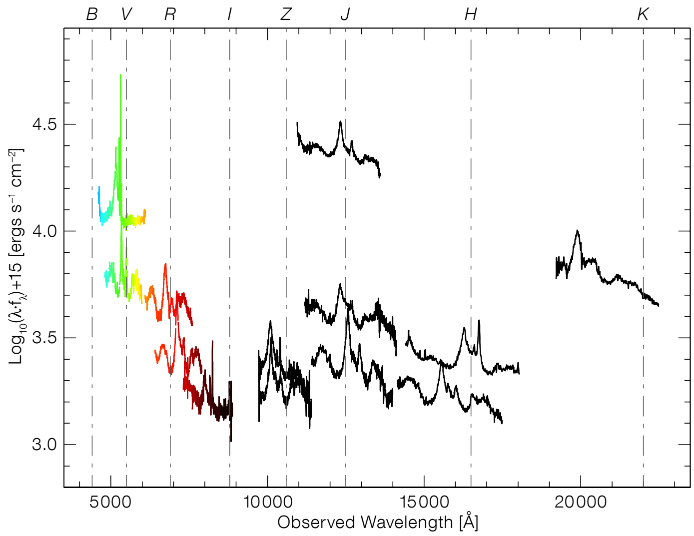

Figure 1. Sample VLT–ISAAC (in black) and optical ground-based spectra of the Hβ region plotted at their redshifted wavelengths. Photometric windows are labelled at the top.

Do quasar spectra change with z and luminosity?

Our samples are ideal for comparing spectra over 6 dex in source luminosity. Figure 2 shows median composite spectra for six luminosity bins ($\log L_{bol} = 43–49$, L_{bol} in units of ergs^{-1}). We find no luminosity correlations in our low redshift samples — consistent with earlier results (Boroson & Green, 1992; Sulentic et al., 2000a; 2004; 2007) that source luminosity is orthogonal to Eigenvector 1 correlations involving FWHM Hβ. Figure 2 shows Pop. A and B composite spectra separately and in fact this 4DE1-inspired distinction is necessary in order to reveal the most significant change in Hβ. Without such a distinction the only luminosity trend that we find involves a systematic weakening of narrow emission lines ([O III] 4959, 5007 Å) with increasing luminosity (see also Netzer et al., 2004 and Marziani et al., 2009, for a few striking exceptions). While narrow line measures are not part of the 4DE1 parameter set, this line decrease raises the question of whether we are seeing a luminosity or redshift (i.e. source evolution) trend. Previous 4DE1 work (Sulentic et al., 2000ab) motivated the suggestion that Pop. A (and especially NLSy1) represent a young quasar population. This interpretation is favoured because we also observe weaker narrow lines in low-z NLSy1 sources. But why then do we see the same diminution in Pop. B composites?

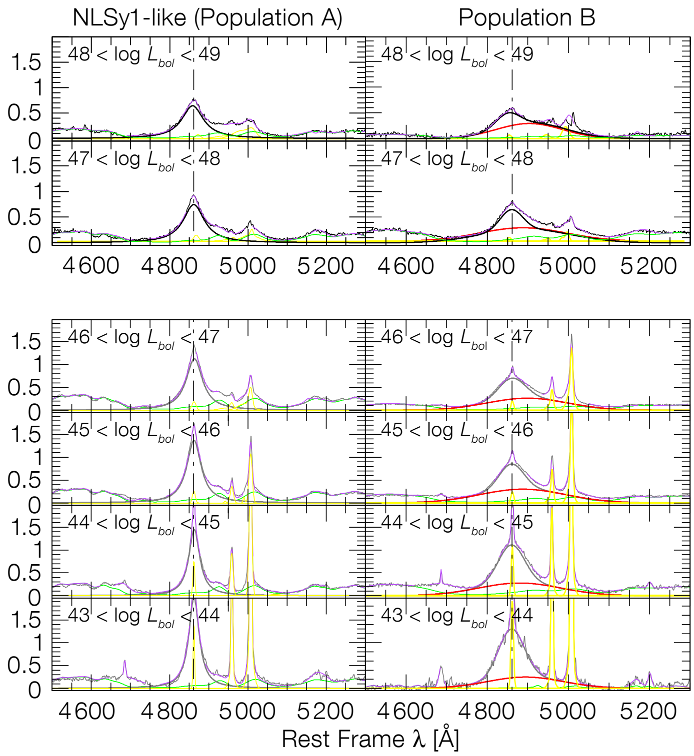

Figure 2. Median composite spectra binned in six integer luminosity intervals. The upper two and lower four bins show the VLT–ISAAC and optical ground-based composites respectively. Population A and B composites are shown for each bin. Fe II contamination (green lines) is always stronger in the Pop. A spectra and a very broad Hβ component (thick red line) is always present in Pop. B spectra.

We find a large spread in FWHM Hβ measures at all redshifts with a well-defined lower boundary that increases from FWHM Hβ ~ 500–1000 km/s at $L_{bol} = 48–49$. No clear change is observed in the upper FWHM boundary. The change in the lower boundary can be seen in Figure 3 where we plot the distribution of FWHM Hβ measures against $\log L_{bol}$. An increase in minimum FWHM with luminosity is expected if Hβ line broadening is dominated by virial motions and if the emissivity-weighted r_{BLR} depends on luminosity following a power-

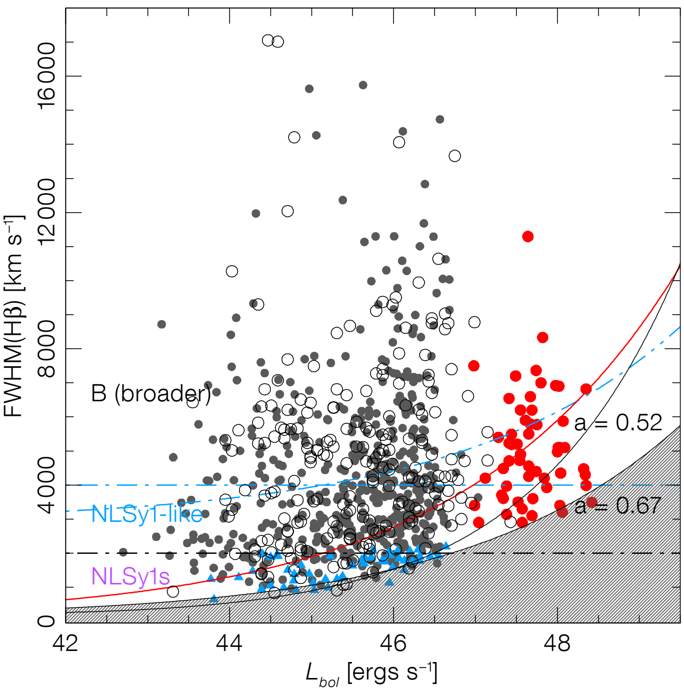

Figure 3. Source FWHM Hβ as a function of bolometric luminosity. Grey dots and open circles show our two low-redshift source samples while red dots indicate the VLT–ISAAC sample. Blue triangles represent additional NLSy1 sources found by Zhou et al. (2006). Horizontal dot-dash lines indicate Pop. A–B and canonical NLSy1-broader source boundaries. Blue dot-dash curve shows modified Pop. A–B boundary based on sources with Lorentzian and Gaussian profiles respectively (Marziani et al., 2009). Two labelled curves show Kaspi relations with exponents α = 0.52 and 0.67. The thick red line indicates FWHM increase with L expected for L/L_{Edd} = 0.15 (assuming α = 0.67). Shaded area is an apparent zone of avoidance for broad-line AGN.

law (r_{BLR} α L_{α}; Kaspi et al., 2005). The exact value of the index is uncertain, but a more pronounced trend is expected in Figure 3 for $\alpha \approx 0.5$, especially at high luminosity (see caption to Figure 3). Irrespective of the correct value for α, the observed trend is one of the few independent lines of evidence supporting the assumption that broadening of Balmer lines is predominantly virial.

Median spectra in Figure 2 show that Pop. A sources retain very similar (Lorentzian) Hβ line profiles, while the same cannot be said for Pop. B sources, where a red asymmetry grows with increasing source luminosity. There is evidence (Marziani et al., 2009) that this asymmetry is a distinct, redshifted component (we call it the very broad line region or VBLR). This extra line component represents a challenge for both physical models of the BLR and for the use of FWHM Hβ as a virial estimator. Could this be the long-sought evidence for infall onto the central engine? Whatever the origin of the VBLR component, our VLT spectra reinforce the evidence that it is real, and that the Pop. A–B dichotomy has a physical meaning, likely involving changes in the structure of the BLR. This dichotomy has a direct implication for the computation of black hole masses — FWHM Hβ is a reliable virial estimator only for Pop. A sources. Only the core (BLR) part of the line appears to be a reliable virial estimator in Pop. B sources (see also Collin et al., 2006).

Comparing black hole masses and Eddington ratios

Figure 4 shows the distribution of M_{BH} as a function of redshift. M_{BH} estimates for the low-z samples span 4 dex and the VLT sample does not increase that range. The yellow region below the curve is inaccessible to useful observations at this time. Measures of $M_{BH} > 5 \times 10^9\ M_{\odot}$ are problematic if the M_{BH} *v.* M_{BULGE} relation is valid at high-z. $M_{BH} \sim 10^{10}\ M_{\odot}$ would imply stellar velocity dispersions ~ 700 km/s and resultant $M_{BULGE} > 10^{10}\ M_{\odot}$, which are not observed. Recent results on the fundamental plane of elliptical galaxies, and on the most massive spheroids at $z < 0.3$, confirm that stellar velocity dispersion measures are always

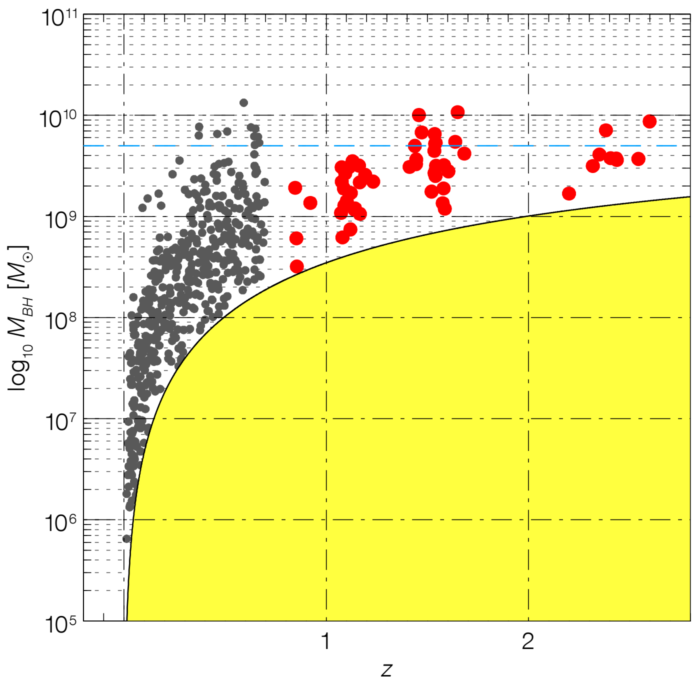

Figure 4. M_{BH} estimates derived from single-epoch FWHM Hβ measures. Red and grey dots represent VLT and low-z SDSS sources respectively. The yellow region is not accessible in our magnitude-limited surveys. The horizontal blue line shows the expected upper limit to the black hole mass of $5 \times 10^9\ M_{\odot}$.

< 500 km/s (Bernardi et al., 2005). Is there real evidence for log M_{BH} values greater than about 9.7?

If we place our confidence in Hβ as the virial estimator, then Figure 2 points toward a way to reduce large M_{BH} values. Our past work, now reinforced by the VLT sample, suggests that all, or most, of these values are overestimates. The VBLR component in Pop. B Hβ profiles shows a large redshift, immediately raising doubts that it arises from a virialised medium. It is safer to assume that the relatively unshifted BLR component is the virial estimator that corresponds most closely to the one used in Pop. A sources. Alternatively one can consider the width of the line part that is responding to continuum changes, which has been estimated for low-z sources (see also Sulentic et al., 2000c). If we use either of these two approaches to infer M_{BH} then most values fall below log M_{BH} = 9.7 (blue dashed line indicated in Figure 4). This would remove any serious challenge to the bulge mass–BH mass relation out to $z \sim 3$.

A fixed bolometric correction to the specific luminosity of each quasar provides the luminosity-to-mass ratio or, equivalently, L/L_{Edd}. This approach is very crude, but a bolometric correction is relatively stable for most sources, with the obvious exception of core-dominated radio-loud quasars. Figure 5 shows the distribution of derived L/L_{Edd} estimates as a function of z. At $z \sim 1$ we start losing quasars with low L/L_{Edd} that are abundant at low z. The loss of sources becomes very serious at $z > 2$ where we are sampling only the highest L/L_{Edd} radiators, which should be equivalent to the low-z NLSy1 sources. Low L/L_{Edd} sources should be present at high-z (numerous if they are young quasars) but an increasing fraction are unobservable. This effect must be carefully considered when studying L/L_{Edd} evolution in any flux-limited sample.

We note that small populations of Eddington or even super-Eddington radiators are present in our sample. We have previously interpreted the low-z sources as oriented near face-on. If line emission arises from a flattened cloud distribution (or accretion disc) where rotational motions dominate, then FWHM Hβ will underestimate virial motions and consequently M_{BH} in sources oriented near face-on. They will appear to be extreme L/L_{Edd} radiators. Reasonable corrections for an assumed face-on orientation will move all of these sources safely below log $L/L_{Edd} \sim 1$ (Sulentic et al., 2000a; Marziani et al., 2003; Ryan et al., 2007). But what of the high-z VLT sources at or near log $L/L_{Edd} \sim 1$ seen in Figure 5? The simplest interpretation places them as high luminosity analogues to lower-z NLSy1s.

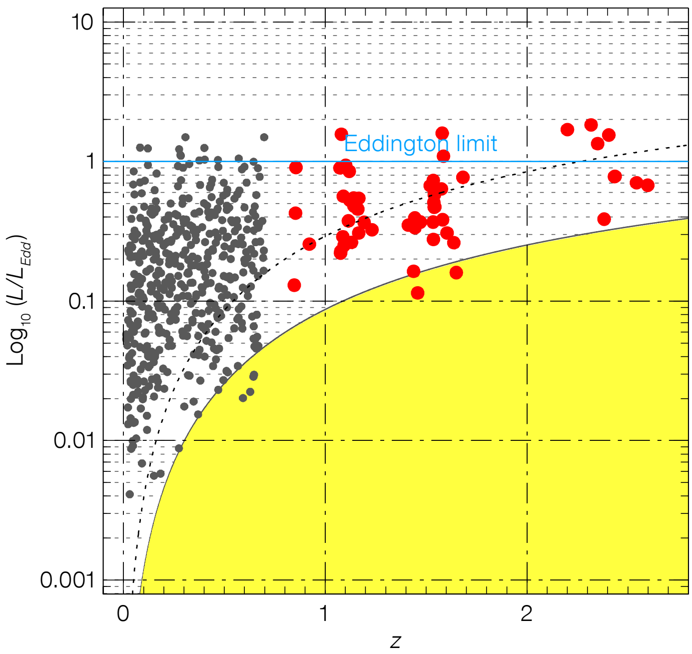

Figure 5. L/L_{Edd} estimates derived from the M_{BH} estimates shown in Figure 4. Red and grey dots represent VLT–ISAAC and low-z SDSS sources respectively. The yellow region is not accessible in our magnitude-limited surveys. Dotted and filled curves represent minimum detectable values of L/L_{Edd} (fixed log M_{BH} = 9.6) for magnitude-limited surveys to m_B = 16.5 and 17.5 respectively.

A modest investment of observing time (equivalent to a single run of 6–7 nights) provided data with unprecedented S/N and resolution and in a redshift range where they were completely absent. The data enabled us to identify several interesting luminosity trends that were not evident in large low-z samples. The ISAAC data reinforce the significance of the Pop. A–B dichotomy by showing that the redshifted VBLR Hβ is the stronger Hβ component in the most luminous Pop. B sources. They also permited a more reliable comparison of M_{BH} and L/L_{Edd} estimates out to $z \sim 3$. The observation of large black hole masses at $z \sim 3$ and beyond (Kurk et al., 2007) suggest that either: a) at least some supermassive black holes grow early in the history of the Universe; or b) rotational motions no longer dominate the Hβ line profile. Since iron enrichment and black hole growth require predictable timescales, extension of observations to high-z may eventually provide intriguing tests of the current cosmological scenario. It is premature to say whether the lack of spectral evolution poses problems for the concordance cosmology.

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