High-redshift quasars along the main sequence*,**,  

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ABSTRACT

Context. The 4D Eigenvector 1 empirical formalism (4DE1) and its main sequence (MS) for quasars has emerged as a powerful tool for organising the diversity among quasar populations, as several key observational measures and physical parameters are systematically changing along it.

Aims. Trends revealed by 4DE1 are very well established to explain all the diverse characteristics seen in low-redshift quasar samples. Nevertheless, the situation is far less clear when dealing with high-luminosity and high-redshift sources. Here, we aim to evaluate the behaviour of our sample of 22 quasars at high redshift (2.2 ≤ z ≤ 3.7) and high luminosity (47.39 ≤ L_{bol} ≤ 48.36) in the context of the 4DE1.

Methods. Our approach involves studying quasar physics through a spectroscopic exploration of UV and optical emission line diagnostics. We used new observations from the ISAAC instrument at ESO-VLT and primarily from the SDSS to cover the optical and the UV rest-frames, respectively. The emission lines were characterised both via a quantitative parametrisation of the line profiles and a decomposition of the emission line profiles using multicomponent fitting routines.

Results. We provide spectrophotometric properties and line profile measurements for Hβ+[O III]λλ4959,5007, as well as Si IVλ1397+O IVλ1402, C IVλ1549+He IIλ1640, and the 1900 Å blend (including Al IIλ1860, Si IIλ1892, and C IIIλ1909). For six out of the 22 objects, a significantly blueshifted component on the Hβ profile is present. In 14 out of 22 cases, an Hβ outflowing component associated with [O III]λλ4959,5007 emission line profiles show blueshifted velocities higher than 250 km s^{-1}. We find extremely broad [O III]λλ4959,5007 emission that is comparable to the width of Hβ broad profile in some highly accreting quasars. The [O III]λλ4959,5007 and C IVλ1549 blueshifts show very high amplitudes and a high degree of correlation. The line widths and shifts are correlated for both [O III]λλ4959,5007 and C IVλ1549, suggesting that emission from outflowing gas is providing a substantial broadening effect to both lines. Otherwise, the links between C IVλ1549 centroid velocity at half intensity (c(1/2)), Eddington ratio (L/L_{Edd}), and bolometric luminosity are found to be in agreement with previous studies of high-luminosity quasars.

Conclusions. Our analysis suggests that the behaviour of quasars of very high luminosity all along the main sequence is strongly affected by powerful outflows involving a broad range of spatial scales. The main sequence correlations remain valid at high redshift and high luminosity even if a systematic increase in line width is observed. Scaling laws based on UV Al IIλλ1860 and Hβ emission lines are equally reliable estimators of M_{BH}.

Key words. quasars: general – quasars: emission lines – quasars: supermassive black holes

1. Introduction

The nature of the many differences seen in quasar spectra has been a key topic of interest in recent years and it continues to be a topic of active discussion. One of the first successful attempts to define the systematic trends of quasar spectra was carried out by Boroson & Green (1992). These authors organised the relations between the optical and radio spectral ranges into an Eigenvector 1 scheme based on studies of the 80 quasars from the Palomar-Green sample (Schmidt & Green 1983) and using a principal component analysis (PCA). This scheme primarily considers the anticorrelation seen between the optical Fe II strength and peak intensity of the [O III]λ5007 emission line as well as the full width at half maximum (FWHM) of the broad component of Hβ (HβFWHM, typically ≥4000 km s^{-1}). A more over-arching possibility for the arrangement of the individual characteristics found in the quasar spectra has been suggested by S坐落ntic et al. (2000a), taking into account several observational measures in the optical, UV, and X-ray spectral ranges as well as physical parameters such as outflow relevance and accretion mode. According to those authors, it is possible to organise the quasar diversity into a fourth dimensional (4D) correlation space known as Eigenvector 1 (4DE1).

One of the four key parameters considered by the 4DE1 is the FWHM of the Hydrogen Hβ broad component. Since the emission of Balmer lines like Hβ are thought to be arising from the quasar broad line region (BLR), this parameter can be used to measure black hole mass assuming gas to be virialised (Collin-Souffrin & Lasota 1988; Small & Blandford 1992; Marziani et al. 1996; McClure & Jarvis 2002; McClure & Dunlop 2004; S坐落ntic et al. 2006a; Assef et al. 2011; Shen 2013;...
Gaskell & Harrington 2018, and references therein). In addition, 4DE1 also considers the ratio between the intensities of the blend of Fe II emission lines at 4570 Å and Hβ (R_{Fe II} = I(Fe II)/I(Hβ)), which can be used for the estimation of physical properties of the BLR such as the ionisation state, the electron density, and the column density of the ionised gas (Ferland et al. 2009; Panda et al. 2020).

The other parameters of the 4DE1 are the blueshifts of high-ionisation lines (HILs) with respect to the quasar systemic redshift and the soft X-ray photon index (I_{soft}). Examples of HILs include the CIV 1549 emission line and they are considered a strong diagnostic of outflows; there is also some evidence that the optical and UV properties are related (Bachev et al. 2004; Du et al. 2016; Śniegowska et al. 2020). Similarly, the equivalent width of the optical Fe II contribution is seen as a measure of the thermal emission from the accretion disc (Singh et al. 1985; Walter & Fink 1993). The R_{Fe II}, soft X-ray photon index, and the line width of Hβ are also significantly correlated among themselves (Wang et al. 1996; Boller et al. 1996; Sulentic et al. 2000b).

The distributions of the detection of low-redshift (z ≤ 0.8) quasars in the optical plane of the 4DE1 – defined by FWHM(Hβ_{PopC}) versus R_{Fe II} and referred to as the main sequence (MS) of quasars – have given rise to the identification of two main populations with very significant differences among their spectra (Zamfir et al. 2010). Population A quasars show low FWHM (usually ≤4000 km s^{-1}) and a wide range of R_{Fe II}, while Population B sources present a very wide range of FWHM(Hβ_{PopC}) but usually small R_{Fe II} (≤1). Marziani et al. (2018) summarised more than 15 yr of discussion on the empirical parametrisation of the quasar properties and their trends as well as the ways physical parameters are related to the accretion rate and feedback seem to be changing along the MS, going from quasars with low Fe II emission and high black hole mass (≥10^{7} M_⊙, Pop. B) to the extreme Pop. A, xA (Martínez-Aldama et al. 2018), with strong Fe II emission (R_{Fe II} > 1) and strong blueshifts in HILs such as CIV 1549, indicating strong wind effects on the quasars (i.e. ‘wind-dominated’ sources, Richards et al. 2011).

The Eddington ratio as well as the orientation effect are seen as key properties in the MS context (Sulentic et al. 2000a; Marziani et al. 2001; Boroson 2002; Shen & Ho 2014; Sun & Shen 2015). The R_{Fe II} parameter along with the Hβ_{PopC} FWHM can be associated with L/L_{Edd} (Marziani et al. 2001; Panda et al. 2019). Low values of the L/L_{Edd} (typically ≤0.2) are usually found in Pop. B sources, while Pop. A sources are found to be high accretors (in extreme cases reaching L/L_{Edd} ≥ 1). Consequently, sources with the highest R_{Fe II} are thought to be the ones with the highest Eddington ratios. Consistent results were also reported by Du et al. (2016), denoting the strong correlation found between the Eddington ratio, shape of the broad profile of the Hβ emission line, and the flux ratio I(Hβ)/I(Fe II) as the fundamental plane of accreting black holes. According to these authors, the shape of both Lorentzian and Gaussian profiles may reveal details on the BLR dynamic and may be different depending on the Eddington ratio (cf. Collin et al. 2006; Kollatschny & Zetzl 2011). Regarding the width of the emission line profiles, the broadest sources that are more Gaussian-like due to a redward asymmetry can be seen as the sum of two Gaussians (usually a BC and a very broad component, VBC) and the sources that present a VBC, usually with FWHM > 7000 km s^{-1}, are the ones displaying lower Eddington ratios (Marziani et al. 2003, 2019). However, the line width is believed to be highly influenced by source orientation and the Eddington ratio (Marziani et al. 2001; McLure & Jarvis 2002; Zamfir et al. 2008; Panda et al. 2019). Since it is likely that Hβ lines are emitted by flattened systems, orientation may affect the FWHM(Hβ), going from broader (bigger θ, with θ indicating the inclination of the source with respect to the line-of-sight) to narrower (smaller θ) profiles.

Of special relevance is also the issue of sources that are radio-loud. Only about 10% of quasars are strong emitters in radio. Zamfir et al. (2010) analysed ~470 low-redshift (z ≤ 0.8) quasars from the SDSS DR5 (Adelman-McCarthy et al. 2007) and found that in general the radio-loud sources are located in the Pop. B domain of the MS, while the radio-quiet are found in both populations. The location of the radio-loud (RL) quasars seems to indicate different properties with respect to a large fraction of the radio-quiet (RQ) sources. However, the fact that the RQs are distributed in both populations (A and B) complicates the interpretation. For instance, radio-loud and a large fraction of radio-quiet quasars both present strong asymmetries towards red wavelengths in the emission line profiles (Marziani et al. 1996; Punsly 2010). The paucity of radio-loud Pop. A sources at low-z implies that the Eddington ratio and the black hole mass distributions are different for radio-quiet and radio-loud sources matched in redshift and luminosity (Woo & Urry 2002; Marziani et al. 2003; Fraix-Burnet et al. 2017). In the two cases, the radio-quiet quasars are the ones that usually present smaller masses and larger Eddington ratio. This is not necessarily true for sources at high redshift (Sikora et al. 2007; Marinello et al. 2020; Diana et al. 2022).

The 4DE1 formalism and especially the MS represent the most effective way to distinguish quasars according to their BLR structural and kinematic differences. It has been extensively analysed in samples at z < 0.8 (e.g. Zamfir et al. 2010; Negrete et al. 2018). Trends among the optical plane of the 4DE1 and the L/L_{Edd} (e.g. sources with strong L/L_{Edd} are usually found to have strong R_{Fe II}) are also seen in high-luminosity high- and intermediate-redshift sources (z ≥ 2 and L ≥ 47, Yuan & Wills 2003; Netzer et al. 2004; Sulentic et al. 2004). However, high-z quasar samples that have been studied including NIR observations of the Hβ spectral range are relatively few (e.g. McIntosh et al. 1999; Capellupo et al. 2015; Coatan et al. 2016; Bischetti et al. 2017; Vietri et al. 2018, 2020; Matthews et al. 2021). One of the studies of high-z quasars under this context was performed by Marziani et al. (2009, hereafter M09). These authors analysed the optical region of 53 Hamburg-ESO sources in a redshift range of z = 0.9–3.0 using VLT ISAAC spectra (Sulentic et al. 2004, 2006a, M09). Additional UV spectra were obtained for some of these sources and the results are reported by Sulentic et al. (2017, hereafter S17). The authors found that both Pop. A and Pop. B quasars present evidences of significant outflows at high redshift while at low z only Pop. A sources tend to show strong contribution of outflowing gas. Extreme Pop. A quasars (xA) in a redshift range of z = 2.0–2.9 and with an averaged bolometric luminosity of log L ~ 47 [erg s^{-1}] have been analysed in details on the UV region by Martínez-Aldama et al. (2018) using GTC spectra. These authors found that the xA sources at high z share the same characteristics of the sources at low redshift, albeit with the higher outflow velocities (reaching values of ~4000 km s^{-1}).

In this paper, we report new observations from VLT/ISAAC for 22 high-redshift and high-luminosity quasars, along with a data analysis of the UV and optical regions along the main sequence and discussion. Our goal is to improve the sampling of the MS and the understanding of high-z, high-luminosity quasars. To do so, we take advantage of previous high-
low-\( z \) samples and perform a comparison between the different data under the 4DE1 context. Details on the sample and on the observations are presented in Sects. 2 and 3. The procedures and the approach followed during the line decomposition are presented in detail in Sect. 4. Results on the complete analysis of both optical (H\( \beta \)+[O III], \( \lambda \lambda 4861,5007 \)) and UV (Si IV, \( \lambda 1392,1402,1549 \), and the 1900 Å blend) regions are reported in Sect. 5. Additional discussions are provided in Sect. 6. In Sect. 7, we list the main conclusions of our work.

2. The sample

Our sample consists of 22 quasars with high redshift, going from \( z = 2.2 \) to \( z = 3.7 \), and with high luminosity (47.39 \( \lesssim \log L_{\text{bol}} \lesssim 48.36 \) [erg s\(^{-1}\)]), including both radio-loud and radio-quiet sources that were observed under the ESO programmes 083.B-0273(A) and 085.B-0162(A). These sources were selected from the Hamburg-ESO survey (HE, Wisotzki et al. 2000), which consists of a flux-limited \((m_V \approx 15.7)\), colour-selected sample with a redshift range \( 0 \lesssim z \lesssim 3.2 \). Our sample covers a redshift that allows for the detection and observation of the H\( \beta \)+[O III], \( \lambda \gamma 4861,5007 \) region through the transparent window in the near-infrared with the ISAAC spectrograph at VLT (Sulentic et al. 2006a, 2017). There is also a cut in \( \delta \) at \( +25^\circ \) due to the geographic location of the telescope. Table 1 presents the main properties of our sample, reporting the source identification according to the different catalogues (Col. 1); right ascension and declination at J2000 coordinates (Cols. 2 and 3, respectively); redshift estimated as explained in Sect. 2.1 (Col. 4); redshift uncertainties (Col. 5); the H- or K-band (depending on the range of the spectrum) apparent magnitude \( m_H \) or \( m_K \) from the 2-MASS catalogue (Col. 6); the restframe (\( H \) or \( K \), Col. 7); the \( i \)-band absolute magnitude \( M_i \) (Col. 8) estimated for our data; the apparent magnitudes of Véron-Cetty & Véron (2010; Col. 9); the radio flux in mJy (Col. 10) in the frequency of the survey listed in Col. 11; radio classification according Ganci et al. (2019) is shown in Col. 12 and explained in Sect. 3.3. The \( k \)-correction used is the one available on Richards et al. (2006) for sources with similar redshift and the galactic extinction were collected from the DR16 catalogue (Lyke et al. 2020). The luminosity distance was computed from the redshift using the approximation of Sulentic et al. (2006a), valid for \( \Delta m = 0.3, \Omega_\Lambda = 0.7 \), and \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

For all sources, we have computed synthetic magnitudes \( H \) or \( K \) from our flux-calibrated spectra, and we have compared them with the 2MASS \( H \) - and \( K \)-band apparent magnitudes. In cases in which the difference between our \( m \) synthetic magnitudes and the 2MASS catalogue magnitudes is higher than 0.5 mag we use the \( m \) from 2MASS (these sources are identified in Table 1). Also, in one very special source (B1422+231) a magnification correction is applied lowering the flux by a factor of 6.6, which leads to a change in the magnitude, since this source is a gravitationally lensed quasar with four images (Patnaik et al. 1992; Assef et al. 2011; see Appendix A for notes on individual objects). Apart from the well-known lensed quasar B1422+231, our sample includes other quasars known or suspected to undergo micro-lensing: SDSSJ141546.24+112943.4 (Sluse et al. 2012; Takahashi & Inoue 2014) and some candidates, as [HB89] 0029+073 (Jaunsen et al. 1995), but we did not apply any magnitude correction for lenizing on these sources.

2.1. Redshift estimations and sample location in the Hubble diagram

Redshift measurements were based on the H\( \beta \) emission line profile and were obtained from the observed wavelength of the H\( \beta \) narrow component \((FWHM \lesssim 1000 \text{ km s}^{-1}\)). The values are reported in Table 1. In the case of HE 0001-2340 and SDSSJ120831.56-063222.5 the redshift was estimated through the [O III],\( \lambda 5007 \) emission line, due to the difficulty of isolating a
narrow component of Hβ. Before performing the spectral analysis, as described in Sect. 4, both optical and UV spectra are set at rest-frame using the IRAF task dopcor.

Figure 1 shows the location of the objects of the sample (pink spots) in the i-band absolute magnitude $M_i$ versus redshift plane. Our sample as well as the comparison samples (defined in Sect. 2.2) are located at the high end of the luminosity distribution when compared with the SDSS DR16 data (grey spots, Lyke et al. 2020). Moreover, some of our sources are well located within the region with the highest values of the SDSS redshift distribution for quasars.

2.2. Comparison samples

We chose comparison samples that include high and low redshifts, as well as high- and low-luminosity sources that have been studied in the recent literature, as follows:

Low-z SDSS sources. Zamfir et al. (2008, 2010) analysed ~470 low-redshift ($z \leq 0.7$) quasars with high signal-to-noise ($S/N \sim 29$) ratio optical spectra observed with the Sloan Digital Sky Survey data release (DR) 5 (Adelman-McCarthy et al. 2007), including both radio-loud and radio-quiet sources. This sample covers a wide range of bolometric luminosity, going from $\log L_{bol} \approx 43$ to $\log L_{bol} = 47$ erg s$^{-1}$.

High-luminosity Hamburg-ESO sample (hereafter, HEMS). Sulentic et al. (2004, 2006a) and M09 obtained, using the VLT-ISAAC camera, Hβ region measurements for a sample of 53 high-redshift high-luminosity objects, selected from the Hamburg-ESO survey. The sources are extremely luminous (47 $\leq L_{bol} \leq 48$) and are located in a redshift range of 0.9 $\leq z \leq 3.1$. We use these data as comparison sample at high $L_i$ for both Hβ and [OIII] lines. For the UV region we use the results provided by S17, who studied 28 quasars of the previous sample, and from which they obtained CIV1549 observations with the VLT and TNG telescopes. The redshift range of the HEMS is $1.4 \leq z \leq 3.1$ and a typical bolometric luminosity is $L_{bol} \approx 10^{47.5}$ erg s$^{-1}$. The location of the HEMS in the Hubble diagram is similar to the one of our data (Fig. 1) in terms of absolute magnitudes, although a large fraction of HE sources displays $1 \leq z \leq 2$.

Low-luminosity FOS data. The low-luminosity Faint Object Spectrograph (FOS) comparison sample was selected from Sulentic et al. (2007, S07 from now on), where the authors analysed the CIV line parameters. Marziani et al. (2003, hereafter M03) provide measurements on the Hβ emission line for most sources in this sample. The typical bolometric luminosity of this sample is $\log L_{bol} \approx 45.6$ [erg s$^{-1}$] and a redshift range $z \leq 0.5$.

3. Observations and data

3.1. Near-infrared observations and data reduction

Spectra were taken in service mode in 2009 and 2010, with the infrared spectrometer ISAAC, mounted at the Nasmyth B focus of VLTI-U1 (Antu) until August 2009, and later at the Nasmyth A focus of VLTI-U3 (Melipal) at the ESO Paranal Observatory. Table 2 summarises the NIR observations, listing the date of observation (Col. 2), used grating (Col. 3), individual detector integration time (DIT) in seconds (Col. 4), range of air mass of the observations (Col. 6), number of exposures with single exposure time equal to DIT (Col. 5), range of air mass of the observations (Col. 6), and the averaged seeing (Col. 7). When the source was observed more than once (HE 0001$-$2340, [HB89] 0029+073, CTQ 0408, SDSSJ161458.33+144836.9, SDSSJ212329.46$-$005052.9, and PKS 2126$-$15), we combine the individual spectra to obtain a median weighted final spectrum for the analysis. Spectral resolutions are $FWHM = 16$ Å in the $H$ band and $FWHM = 22$ Å in the $K$ band.

| Source         | Date obs. (start) | Band | DIT (s) | N$_{exp}$ | Airmass start-end | Averaged seeing (s) |
|----------------|-------------------|------|---------|-----------|------------------|--------------------|
| HE 0001$-$2340 | 2010-07-06        | H    | 100     | 12        | 1.05$-$1.02       | 1.03               |
| [HB89] 0029+073 | 2010-07-24        | H    | 100     | 12        | 1.03$-$1.01       | 0.55               |
| SDSSJ114358.52$+$052444.9 | 2010-07-08 | H    | 100     | 12        | 1.06$-$1.12       | 1.44               |
| SDSSJ115954.33$+$021921.1 | 2010-04-05 | K    | 100     | 12        | 1.43$-$1.25       | 1.08               |
| SDSSJ210247.90$+$02630.2 | 2010-04-05 | K    | 100     | 12        | 1.25$-$1.19       | 0.49               |
| SDSSJ210212.33$+$124037.1 | 2010-05-04 | H    | 100     | 12        | 1.19$-$1.18       | 1.31               |
| Q 1410+096    | 2010-04-20        | K    | 100     | 12        | 1.11$-$1.12       | 0.51               |
| SDSSJ141546.24$+$112943.4 | 2010-05-04 | K    | 100     | 12        | 1.24$-$1.26       | 0.50               |
| B1422+231     | 2009-04-13        | K    | 100     | 12        | 1.50$-$1.48       | 0.98               |
| SDSSJ153830.55$+$085517.0 | 2010-04-05 | K    | 100     | 12        | 1.20$-$1.24       | 1.14               |
| SDSSJ161458.33$+$144836.9 | 2009-07-08 | H    | 100     | 12        | 1.33$-$1.30       | 1.35               |
| PKS 1937$-$101 | 2009-09-03        | K    | 100     | 12        | 1.13$-$1.23       | 1.07               |
| PKS 2000$-$330 | 2009-08-31        | K    | 100     | 12        | 1.43$-$1.89       | 2.03               |
| SDSSJ210524.49$+$000407.3 | 2010-07-23 | H    | 100     | 12        | 1.29$-$1.45       | 1.80               |
| SDSSJ210831.56$-$063022.5 | 2009-06-19 | H    | 100     | 12        | 1.07$-$1.18       | 0.93               |
| SDSSJ212329.46$-$005052.9 | 2010-07-08 | H    | 100     | 12        | 1.12$-$1.18       | 0.48               |
| PKS 2126$-$15 | 2009-09-01        | K    | 100     | 12        | 1.41$-$1.27       | 0.90               |
| PKS 2126$-$15 | 2010-06-09        | K    | 100     | 12        | 1.84$-$2.36       | 1.41               |
| SDSSJ235808.54$+$012507.2 | 2010-06-21 | K    | 100     | 12        | 1.26$-$1.12       | 1.07               |

Figure 1. Location of the complete sample in the Hubble diagram (pink spots). Gray dots represent a random subsample of the DR16 catalogue from Lyke et al. (2020) and green, yellow, and blue dots represent the comparison samples defined in Sect. 2.2.
Reductions were performed using standard IRAF routines. Several spectra for each source were taken, nodding the telescope between two positions (nodding amplitude = 20′). Each obtained frame was divided by the flat field provided by the ESO automated reduction pipeline. The 1D spectra were extracted using the IRAF program ‘apall’. Cosmic ray hits were eliminated by interpolation using a median filter, comparing the affected spectrum with the other spectra of the same source.

For each position along the slit, a 1D xenon/argon arc spectrum was extracted from the calibration lamp frame, using the same extraction parameters as the corresponding target spectrum. The wavelength calibration was well modeled by 3rd order Chebyshev polynomial fits to the positions of 15 – 30 lines, with rms residuals of 0.3 Å in s/H and 0.6 Å in s/K. The wavelength calibration is usually affected by a small 0-order offset caused by grism and telescope movement, because the arc lamp frames were obtained in the daytime. A correction for these shifts was obtained by measuring the centroids of 2 – 3 OH sky against the arc calibration and calculating the average difference, which reached at most 2 – 3 pixels in either direction. Once matched with the corresponding arc calibrations, the individual spectra of each source were rebinned to a common linear wavelength scale and stacked.

The spectra of the atmospheric standard stars were extracted and wavelength-calibrated in the same way. All clearly identifiable stellar features (H and He I absorption lines) were eliminated from the stellar spectra by spline interpolation of the surrounding continuum intervals. Each target spectrum was then divided by its corresponding standard star spectrum in order to correct for the atmospheric absorption features. This was achieved with the IRAF routine ‘telluric’, which allows to optimise the correction with slight adjustments in shift and scaling of the standard spectrum. The correct flux calibration of each spectrum was achieved by scaling it according to the magnitude of the standard star and to the ratio of the respective DITs. Because the seeing often exceeded the width of the slit, significant light loss occurred and, therefore, the absolute flux scale of the spectra is not to be considered as accurate. However, in this long-wavelength range we consider the light losses to be independent of wavelength (i.e. we assume that differential atmospheric refraction is negligible) and thus they are not expected to affect the relative calibration of the spectra. We carried out an a posteriori evaluation of the absolute flux calibration uncertainty performing a comparison between the H/K-band magnitudes estimated by convolving the H/K filter with the observed spectrum and the H/K magnitudes in NED. The differences are smaller than 0.5 mag, except for SDSSJ132012.33+142037.1, SDSSJ141546.24+112943.4, and SDSSJ153830.55+085517.0, where a correction factor –0.880 ± 0.176 mag was applied.

3.2. UV

We found useful UV spectra (i.e. those including at least one of the three UV regions of our interest) for the 15/22 sources that are listed in Table 3, where we also list in Col. 2 the database and reference from which each spectrum was obtained and then the broad absorption line (BAL) quasars in Col. 3. We report the BAL sources as the analysis of the region in which the broad absorptions are located should be taken with care, once it demands the addition of absorption components in the fitting routine. The other seven quasars do not have useful UV spectra, either because they are old spectra that are not digitally available and have low S/N not suitable for accurate profile fitting, or because they do not include any of the three UV regions we want to analyse (Si IV; λ1397 and do not affect the other UV emission lines that we are considering in the fittings.

Table 3. UV spectra information.

| Source                  | UV spect. | Comments |
|-------------------------|-----------|----------|
| SDSSJ005700.18+143737.7 | BOSS      |          |
| SDSSJ114358.52+052444.9 | BOSS      |          |
| SDSSJ115954.33+201921.1 | SDSS      |          |
| SDSSJ120147.90+120303.2 | BOSS      |          |
| SDSSJ132012.33+142037.1 | BOSS      |          |
| SDSSJ153831.78+050522.8 | BOSS      |          |
| Q 1410+096             | SDSS      | BAL      |
| SDSSJ141546.24+112943.4 | SDSS      | BAL      |
| SDSSJ153830.55+085517.0 | BOSS      | BAL      |
| SDSSJ161458.33+144836.9 | BOSS      |          |
| PKS 2000–330           | Barthen et al. (1990) |
| SDSSJ210524.49+000407.3 | SDSS      | BAL      |
| SDSSJ210831.56–063022.5 | SDSS      |          |
| SDSSJ212329.46–005029.2 | BOSS      |          |
| SDSSJ235808.54+012057.2 | BOSS      |          |

Notes. In this case, there is only a small but significant absorption close to Si IV;λ1397 and do not affect the other UV emission lines that we are considering in the fittings.

3.3. Radio data

The radio fluxes presented in Table 1 were collected from the 1.4-GHz NRAO VLA Sky Survey (NVSS, Condon et al. 1998) and from the VLA FIRST Survey (Gregg et al. 1996; Becker et al. 1995). The flux in radio is reported for seven of our sources and in the case the object is not detected we provide an upper limit to the flux, which corresponds to the detection limit (≈5 times the rms in both FIRST and NVSS catalogue) at the position of the source. In the case of CTQ0408, there is no coverage either in the FIRST survey or in the NVSS survey. The radio flux for this source is obtained at 408 MHz from the Sidney University Molonglo Sky Survey catalogue (Mauch et al. 2003). The radio classification is shown in Col. 12 of Table 1 and was determined following Ganci et al. (2019) via the estimation of a modified rest-frame radio loudness parameter \( R_K = f_{\text{radio}}/f_{\text{optical}} \) (Kellermann et al. 1989), defined as the ratio between the specific flux at 1.4 GHz and in the \( \nu \)-band. Accordingly, our sample is separated into three different ranges: radio-quiet (RQ; \( R_K < 10 \)), radio-intermediate (RI; \( 10 \leq R_K < 70 \)), and radio-loud (RL; \( R_K \geq 70 \)). Of the seven sources with radio detection, three of them (CTQ0408, SDSSJ141546.24+112943.4, and SDSSJ210524.49+000407.3) are classified as radio-intermediate. The radio-loud sources from our sample are B1422+231, PKS 1937–101, PKS 2000–330, and PKS 2126–15, about 20% of the sources of this sample.
plan to carry out a similar spectroscopic study focused on RL quasars to supplement those listed in Table 1 in a forthcoming paper.

4. Spectral analysis

4.1. Optical range: Multicomponent fitting

4.1.1. Hβ

The multicomponent fits were performed, after the spectra were set at rest-frame, using the SPECFIT routine from IRAF (Kriss 1994). This routine allows for simultaneous minimum-$\chi^2$ fit of the continuum approximated by a power-law and the spectral line components yielding FWHM, peak wavelength, and intensity of all line components. In the optical range, we fit the Hβ profile as well as the [O\textsc{iii}] λ4959, 5007 emission lines and the Fe\textsc{ii} multiplets for the 22 objects.

Our approach includes the continuum (a power law), a semi-empirical scalable Fe\textsc{ii} emission template and the emission line components to fit the Hβ profile as well as the [O\textsc{iii}]λ4959, 5007 emission lines and the Fe\textsc{ii} multiplets for the 22 objects.

An approach similar to the one used for Hβ is also followed for the [O\textsc{iii}]λ4959, 5007 emission line profiles. The [O\textsc{iii}]λ4959, 5007 full profile is assumed to be well represented by a Gaussian narrow (FWHM $\leq$ 1200 km s$^{-1}$) component set at rest-frame or shifted to the blue and a semi-broad component (SBC, FWHM typically $\leq$3000 km s$^{-1}$) that usually appears more shifted to the blue ($\sim$1000 km s$^{-1}$, Zhang et al. 2011; Marziani et al. 2016a, 2022a). The NC is modelled as a Gaussian profile for the two populations and in a first approach the NC of both Hβ and [O\textsc{iii}]λ4959, 5007 share the same line width. The blueshifted contributions can be modelled by one or more Gaussian profiles and in some cases the Gaussian needs to be asymmetric towards the blue to account for the line shape, namely, to be a ‘skewed’ Gaussian. The use of a skewed Gaussian has a physical motivation, as it might be associated with bipolar outflow emission in which the receding side of the outflow is obscured. Apart from that, both [O\textsc{iii}]λ4959 and [O\textsc{iii}]λ5007 emission line profiles are assumed to have the same FWHM and shifts, and the intensity ratio between the two lines is kept fixed at 1:3 (Dimitrijević et al. 2007).

4.2. UV range: Multicomponent fitting

Fits were performed for three different regions centred on Si\textsc{iv}λ1397+O\textsc{iv}λ1402, C\textsc{iv}λ1549+He\textsc{ii}λ1640, and the 1900 Å blend that includes the Al\textsc{iii}λ1860 doublet, Si\textsc{iii}λ1892, Si\textsc{ii}λ1816, and C\textsc{iii}λ1909. The UV fittings are presented for 15 sources. The fits were not carried out in cases where the emission lines are strongly affected by BALs. The fittings of the absorption lines are performed in sources in which the presence of these lines allows to clearly see the emission line profile (as in the case of mini-BALs; Sulentic et al. 2006b). The UV blends are fit following the population assignments from the Hβ spectral range. The only exception is SDSSJ153830.55+085517.0, where its UV spectrum cannot be fitted in agreement with its classification as Pop. B in the Hβ region, as highlighted in the Appendix A.

4.2.1. 1900 Å blend

In the UV region corresponding to the 1900 Å blend, the fittings are performed considering the Al\textsc{iii}λ1860 doublet, Si\textsc{iii}λ1892, Si\textsc{ii}λ1816, and C\textsc{iii}λ1909 emission line profiles. Here, Fe\textsc{iii} is especially relevant on the red side of the 1900 Å blend and its modelling was performed using the Vestergaard & Wilkes (2001) empirical template, and following the same approach as for the optical Fe\textsc{ii}. Broad line components of the 1900 Å
blend in Pop. A sources are fitted by Lorentzian profiles while in Pop. B by Gaussian functions (as is the case of Hβ in the optical spectral range), keeping the same (or at least a comparable) FWHM to the broad component of Hβ.

In several Pop. A and more frequently in xA quasars, the FeIII template and the CIII]λ1909 broad component do not adequately reproduce the shape of the red side of the 1900 Å blend. A better model of the CIII]λ1909 region is achieved assuming an additional contribution mostly likely due to the FeII line at 1914 Å. The same approach was employed in Martínez-Aldama et al. (2018).

Regarding the Pop. B sources, the CIII]λ1909 emission line is well represented by the same combination applied for Pop. B Hβ: VBC+BC+NC. The VBC FWHM is expected to be ≥4000 km s⁻¹, and the NC FWHM ~ 1000 km s⁻¹ (there is only one source that shows a significant NC in CIII]). Differently from CIII]λ1909, lines such as the AlIII]λ1860 doublet, SiII]λ1892, and SiIII]λ1816 are assumed not to present a very broad component (Buendia-Ríos et al. 2022). They are fit by only one BC.

4.2.2. CIV λ1549+HeII λ1640

In order to fit the CIV λ1549+HeII λ1640 blend and contamiltion lines within it, we use the approach followed by S17. As in the previous fits, we represent Pop. A profiles of CIV λ1549 and HeII λ1640 by a broad and a blueshifted component. Pop. B are represented by the combination VBC+BC+BLUE. The broad components of CIV λ1549 and HeII λ1640 are fixed at rest-frame and the other components are left free to vary in wavelength. Nevertheless, the FWHM and shapes of HeII λ1640 BC and BLUE are restricted to be equal (or comparable) to the corresponding ones of CIV λ1549. These constraints are physically motivated since both CIV λ1549 and HeII λ1640 are expected to be emitted from the same regions, because of the similar ionisation potential of the parent ionic species. An additional condition is that the broad component (BC) of CIV λ1549 and HeII λ1640 FWHM should be equal or larger to the one of Hβ, following previous works (e.g. Sulentic et al. 2017, and references therein).

4.2.3. SiIV λ1397+OIV λ1402

For the SiIV λ1397+OIV λ1402 emission lines region, we follow the same steps as in the CIV+HeII blend. The SiIV λ1397+OIV λ1402 feature profile is similar to the one of CIV λ1549, and is therefore expected to present BC and blueshifted component similar to those of CIV λ1549. The broad component in this case is also kept at rest-frame and any other necessary component is free to change in all the parameters.

4.3. Analysis of the full profile parameters for the optical and UV regions

Apart from the multicomponent fitting, the Hβ and [OIII] emission line profiles are also characterised through the parametrisation of the full profile by measuring centroids and widths at different fractional intensities (1/4, 1/2, 3/4, and 9/10), as well as asymmetry and kurtosis indexes in order to provide a quantitative description independent of the SPECFIT modelling. In the case of Hβ, the full profile (Hβfull) for Pop. B quasars is represented by BC+VBC plus BLUE when detected. For Pop. A quasars, full Hβ profile consists of BC plus BLUE if an additional blue component is present. For [OIII] we consider NC and one (or more, if needed) blueshifted SBC. Full profile parameters for the UV region are provided for the CIV λ1549 broad emission line, excluding NC.

4.4. Error estimates

Uncertainties in the multicomponent fits were estimated by running Markov chain Monte Carlo (MCMC) simulations, following the approach described in Marziani et al. (2022b) for both optical and UV spectral ranges. Observed spectra were modeled using the components employed in the best fit, with a Markov chain to sample the domain around the minimum χ². The dispersion in the posterior distribution of a parameter was assumed to be its 1σ confidence interval. For the optical range, the errors are around the order of 10% for the FWHM of the Hβ and [OIII]SBC. Larger uncertainties (~30%) are found for the narrow components of both lines and for the blueshifted component of Hβ. Flux uncertainties for strong or sharp emission lines are ~10%, while typical errors for the continuum and FeII are ~5% and ~15% respectively, if FeII is reasonably strong. For the UV, the FWHM uncertainties are between 10% and 15% and errors on intensity measurements are usually ≤10% for the strongest emission line components.

5. Results

5.1. Location in the optical plane of main sequence

After performing the multicomponent fitting, we can locate the sample in the MS optical plane, using the FWHM(Hβfull) as well as the flux ratio of FeII λ1640 and Hβ, RFeII. Figure 3 shows the location of the sources and a comparison between our sample and low- and high-z samples. The grey- and green-shaded areas in the plot indicate the location of low-redshift quasars on the MS, with the xA sources situated on the green shadow.

Our sample shows a slight displacement in the direction of increasing FWHM(Hβ), if compared to low-z samples (e.g. Zamfir et al. 2010, and the shaded area in Fig. 3). There are some Pop. A sources that present a FWHM(Hβfull) ~ 5000 km s⁻¹. The Pop. A-B boundary at FWHM(Hβ) = 4000 km s⁻¹ is reasonable when considering low redshift and, consequently, lower luminosity ranges than those of high-z quasars (Sulentic et al. 2004). However, at high luminosity there is a significant effect on the Hβ profile width that may shift the boundary between Pop. A and B by more than 1000 km s⁻¹ (M09). Up and bottom purple shadows in Fig. 3 indicate, respectively, the Pop. A-B boundary and the minimum FWHM(Hβ) found in a 47 ≤ log Lbol ≤ 48 range that are representative of our sample. Both boundaries were determined following M09.

Of the 22 sources of our sample, 12 are classified as Pop. A and 10 as Pop. B quasars. We found three sources to belong to spectral type (ST) A1; six Pop. A2; three Pop. A3 (extreme A); eight to be Pop. B1; and two Pop B2. The four radio-loud objects (B1422+231, PKS 1937–101, PKS 2000–330, and PKS 2126–15) are identified in Fig. 3 by the blue and red symbols surrounded by a open circle. Three of them are classified as Pop. A and only one PKS 2126–15 is a Pop. B quasar. Of the three radio-intermediate, two (SDSSJ141546.24+112943.4, ST B2; SDSSJ210524.49+000407.3, A3) show significant FeII and an overall spectrum associated with high accretion rates (Ganci et al. 2019; del Olmo et al. 2021; Marziani et al. 2022c). Only CTQ 0408 is classified as B1, with an optical spectrum resembling the powerful jetted sources at low z. The orientation may strongly affect the classification of the sources, especially
in the cases when the FWHM(Hβ) is at the border line of the A-B boundary. Orientation effects could be particularly important in the case of core-dominated RL sources, as the pole-on orientation may imply a narrowing of low-ionisation emission line widths (Wills & Browne 1986; Marziani et al. 2001; Sulentic et al. 2003; Rokaki et al. 2003; Zamfir et al. 2008; Bisogni et al. 2017).

There is just one case of a blatant disagreement between the classification deduced from the optical and UV spectra of the same source: SDSSJ153830.55+085517.0, which is optically classified as Pop. B but presents clearly Pop. A-like profiles in the UV spectrum (see Appendix A.14 and Fig. A.14). In this case, it was necessary to fit the optical as Pop. B and the UV as Pop. A.

5.2. Optical

5.2.1. Hβ

Appendix A shows the full VLTI-ISAAC optical spectra and their respective Hβ+[O III]λ4959, 5007 fittings. Spectrophotometric measurements on Hβ are presented in Table 4. The ST of each source is listed in Col. 2; the specific continuum flux at 5100 Å (in rest-frame) is in Col. 3; equivalent width (EW) of the Hβ and [O III]λ4959,5007 full profiles in Cols. 4 and 5, respectively; and the Fe II prominence parameter ($R_{FeII}$) is listed in Col. 7.

Table 5 reports measurements on the Hβ profile. First we present the parameters obtained through the analysis of the Hβ full broad profile, including FWHM(Hβ\textsubscript{full}), (Col. 2), asymmetry index (Col. 3), kurtosis (Col. 4), and the centroid velocity shifts at $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, and $\frac{9}{8}$ fractional intensity (Cols. 5–8, respectively). In Col. 9, we list the full Hβ line flux (i.e., the flux for all broad line components, BC and VBC and BLUE, whenever appropriate). For each broad component isolated with the SPECFIT analysis we report, from Cols. 10–18, flux normalised by the total flux ($I/I_{tot}$), FWHM, and velocity shift. Then, Col. 19 shows the total flux of the narrow profile (SBC+NC) and from Cols. 20–25 we report $I/I_{tot}$, FWHM, and shift for these components. Additionally, we provide, in the last row of Pop. A and B, respectively, the median values of the measurements, together with the interquartile range.

The centroid velocities are close to the rest-frame wavelength for the majority of Pop. A and only two of the Pop. A quasars present c(1/2) strongly shifted towards the blue with an averaged value of $\approx 271$ km s$^{-1}$. These sources are SDSSJ005700–18+143737.7 (ST A3) and SDSSJ132012.33+142037.1 (A1), both of them presenting a clear blueshifted contribution in Hβ profile. In the case of Pop. B quasars, the centroid velocities are significantly shifted towards the red wing of the profile in every fractional intensity for the majority of the sources, with an averaged c(1/2) value of $\approx 640$ km s$^{-1}$. Even higher values are found for c(1/4); Pop. B present an averaged value of $\approx 1780$ km s$^{-1}$ while Pop. A have $c(1/4) = n 149$ km s$^{-1}$.

Overall, Pop. B sources show FWHM(Hβ\textsubscript{full}) values that are much larger than those of Pop. A, usually $\approx 6000$ km s$^{-1}$. This difference is a direct consequence of the definition of Pop. A and B. The Pop. B asymmetry index is positive and very significantly different from 0, since the contribution of the VBC – which reaches FWHM values $\approx 10000$ km s$^{-1}$ – in all cases represents $\approx 50\%$ of the full emission line profile. In other words, differently from Pop. A sources (in which only a symmetric BC is enough to represent the full profile in the majority of the cases), a second redshifted component is always needed to reproduce the strong red wing of the observed Hβ profile.

Table 4. Spectrophotometric measurements on Hβ.

| Source          | ST     | $I_{F(5100)}$ | EW(Hβ) | EW(OIII) | $R_{FeII}$ |
|-----------------|--------|--------------|--------|----------|------------|
| SDSSJ005700–18+143737.7 | A3     | 2.5 ± 0.3    | 53 ± 6 | 4.5 ± 0.5 | 1.33 ± 0.17 |
| SDSSJ132012.33+142037.1 | A1     | 1.2 ± 0.1    | 74 ± 9 | 19.8 ± 2.4 | 0.31 ± 0.05 |
| SDSSJ135830.55+085517.0 | A2     | 2.2 ± 0.3    | 68 ± 8 | 16.3 ± 2.0 | 0.65 ± 0.10 |
| SDSSJ161548.33+144836.9 | A2     | 2.3 ± 0.3    | 83 ± 9 | 16.8 ± 2.0 | 0.52 ± 0.08 |
| PKS 1937–101   | B1     | 7.6 ± 0.9    | 62 ± 7 | 15.3 ± 1.6 | 0.03 ± 0.01 |
| PKS 2000–330   | A2     | 2.8 ± 0.3    | 59 ± 7 | 15.1 ± 1.8 | 0.62 ± 0.09 |
| SDSSJ210524.49+000407.3 | A3     | 3.9 ± 0.5    | 51 ± 4 | 0.4 ± 3.0  | 1.00 ± 0.16 |
| SDSSJ210831.56–063022.5 | A2     | 1.4 ± 0.5    | 44 ± 6 | 4.7 ± 0.6  | 1.29 ± 0.19 |
| SDSSJ212396.46–005052.9 | A2     | 4.4 ± 0.5    | 34 ± 5 | 5.5 ± 0.7  | 0.96 ± 0.14 |
| SDSSJ213580.58+012507.2 | A2     | 4.7 ± 0.6    | 63 ± 8 | 10.7 ± 1.3 | 0.98 ± 0.20 |

Notes. $^{a}$In units of 10$^{-15}$ erg cm$^{-2}$ Å$^{-1}$.

Fig. 3. Location of our sources through the optical plane of the 4DE1. Pop. A quasars are represented by blue circles and Pop. B by red circles. The radio-loud sources from the sample are surrounded by a circle in the plot. Grey and green regions indicate the distribution of the main sequence of quasars across the 4DE1 optical plane in a low-$z$ context (Marziani et al. 2018). Spectral types (ST) of the MS are labelled according to Sulentic et al. (2002). Blue and red squares indicate high-redshift Pop. A and Pop. B quasars from M09, respectively. Purplish-shaded areas show the luminosity-density boundary between Pop. A and B and the minimum FWHM value for sources with 47 $\leq L_{bol} \leq$ 48 and assuming $\alpha = 0.67$ (Marziani et al. 2009).
Table 5. Results from SPECFIT analysis on Hβ.

| Source          | SDSSJ005700.18 | SDSSJ135831.78 | PKS 1937 | SDSSJ210524.49 | SDSSJ210831.56 | B1422 | SDSSJ114358.52 | SDSSJ115954.33 | SDSSJ141546.24 | SDSSJ153830.55 |
|-----------------|----------------|----------------|----------|----------------|----------------|-------|----------------|----------------|----------------|----------------|
| $\lambda_{\text{FWHM}}$ | 3.10 $\pm$ 0.03 | 3.44 $\pm$ 0.04 | 4.07 $\pm$ 0.05 | 3.62 $\pm$ 0.03 | 3.93 $\pm$ 0.04 | 3.78 $\pm$ 0.04 | 3.61 $\pm$ 0.03 | 3.98 $\pm$ 0.04 | 3.73 $\pm$ 0.03 | 4.05 $\pm$ 0.04 |
| $\lambda_{\text{I}}$ | 1.66 $\pm$ 0.01 | 1.66 $\pm$ 0.01 | 1.66 $\pm$ 0.01 | 1.66 $\pm$ 0.01 | 1.66 $\pm$ 0.01 | 1.66 $\pm$ 0.01 | 1.66 $\pm$ 0.01 | 1.66 $\pm$ 0.01 | 1.66 $\pm$ 0.01 | 1.66 $\pm$ 0.01 |
| $\lambda_{\text{I}}/\lambda_{\text{tot}}$ | 91.1 $\pm$ 0.9 | 91.1 $\pm$ 0.9 | 91.1 $\pm$ 0.9 | 91.1 $\pm$ 0.9 | 91.1 $\pm$ 0.9 | 91.1 $\pm$ 0.9 | 91.1 $\pm$ 0.9 | 91.1 $\pm$ 0.9 | 91.1 $\pm$ 0.9 | 91.1 $\pm$ 0.9 |

Notes. (1) In these columns, we report additional blueshifted components that were included in the Hβ profile. (2) In units of 10$^{-4}$ ergs cm$^{-2}$ s$^{-1}$. (3) In units of 10$^{-8}$ ergs cm$^{-2}$ s$^{-1}$. (4) There is an additional contribution due to small blueshifted components associated with narrow line emission. (5) Full profile centroid velocities and the presence of a BLR component in this case are affected by the location of the continuum.
Semi-broad Hβ blueshifts could be mainly associated with the [O\textsc{iii}]λ4959,5007 SBC. However, in some cases, an additional BLUE Hβ component is needed (see Table 5). In particular, PKS 2126–15 presents a huge BLUE blueshift of \( \approx -4700\) km s\(^{-1}\), associated with a boxy termination of the Hβ blue wing. A second peculiarity of this source is that the Hβ BC is significantly shifted to the blue, down to half maximum, which is at variance with all other Pop. B sources.

The Hβ NC is weak especially in Pop. A (\( \lesssim 0.02 \) of the Hβ line flux), although it is observed in all cases save two Pop. A2 sources (SDSSJ132012.33+142037.1 and Q 1410+096). In Pop. B, the narrow component is somewhat stronger but always \( \lesssim 0.05 \) of the line flux. Given its weakness, the NC is therefore not significantly affecting the flux of any broad component measured in this paper.

**Relation between FWHM(Hβ\text{full}) and FWHM(Hβ\text{BC}).** This work confirms previous studies (e.g. Sulentic et al. 2006a; Marziani et al. 2009, and references therein) that showed that the full Hβ profile of Pop. A can be accounted for mostly by the BC, and that a redshifted VBC seems to be absent in Pop. A but present in Pop. B sources: Table 5 lists centroid and asymmetry index values for Pop. B sources of 1000 \( \lesssim c(\xi) \lesssim 2000\) km s\(^{-1}\) and \( \approx 0.2 \), respectively. For Pop. A these values are \( \lesssim 0\) km s\(^{-1}\) and 0.

The left plot of Fig. 4 shows the relation between the FWHM of the BC and the FWHM of the full profile of Hβ for the two populations. Pop. A and Pop. B sources follow different trends for the ratio \( \xi = \text{FWHM}(\text{Hβ}\text{full})/\text{FWHM}(\text{Hβ}\text{BC}) \). For Pop. A quasars, we obtain \( \xi = 1.00 \) for all sources but four (SDSSJ005700.18+143737.7, SDSSI132012.33+142037.1, SDSSI161458.33+144836.9, and PKS 2000–330, with \( \xi = 0.9 \) due to the presence of a blueshifted component). The ratio \( \xi \) for Pop. B is only \( \approx 0.76 \), indicating that the Pop. B Hβ full profile is less representative of the BC than the Pop. A sources. Similar results were also shown by Marziani et al. (2013): they obtain \( \xi = 1.00 \) for Pop. A and \( \approx 0.78 \) for Pop. B quasars. In our sample Pop. B sources usually present a very strong and wide VBC component that accounts for \( \approx 0.57 \) of the profile, with a mean FWHM of 11 240 km s\(^{-1}\). Meanwhile, as mentioned, the Pop. A sources in general are well represented by only a BC. This also seems to be true for the radio-loud Pop. A sources from the sample.

Clear distinctions between Pop. A and Pop. B are also seen in the center and left panels of Fig. 4, which present the \( c(1/2) \) and \( c(1/4) \) vs. FWHM(Hβ\text{full}) relations, respectively. Pop. A sources show in general no shift, within the uncertainties, or a negative value of velocity centroids in the case of the 4 sources with a BLUE component (with average centroid values at 1/2 and 1/4 of \( -167 \) and \( -312 \) km s\(^{-1}\), respectively). On the other hand, Pop. B sources always present positive velocities for \( c(1/2) \) and \( c(1/4) \), with a mean value of 658 and 1929 km s\(^{-1}\), respectively, as a consequence of a very strong VBC. The VBC individually has a median velocity shift of \( \approx 3000\) km s\(^{-1}\), in a range from \(-150\) to \( 4000\) km s\(^{-1}\). These results are in complete agreement with previous results (e.g. Wolf et al. 2020, and references therein).

5.2.2. [O\textsc{ii}]λ4959,5007

High-ionisation lines like [O\textsc{iii}]λ4959,5007 are seen as one of the main detectors of outflowing gas in radio-quiet sources (Zamanov et al. 2002; Komossa et al. 2008; Zhang et al. 2011; Marziani et al. 2016a). In the case of radio-loud sources, narrow-line outflowing gas has been associated with jets through the blueshifted line components (Capetti et al. 1996; Axon et al. 2000; Bicknell 2002; Kauffmann et al. 2008; Best & Heckman 2012; Reynolds & Feinstein 2013; Jarvis et al. 2019; Berton & Järvellä 2021). Outflows are also detected in Hβ. Usually, the blueshifted components on the Hβ profile are related to those found for the [O\textsc{iii}]λ4959,5007 lines (Carniani et al. 2015; Cresci et al. 2015; Brusa et al. 2015; Marziani et al. 2022a). The results obtained for [O\textsc{iii}]λ5007 full profile and individual components are reported in Table 6. We present FWHM (Col. 2), asymmetry (Col. 3), kurtosis (Col. 4), and the centroid velocities at 1/2 and 9/10 intensities (Cols. 5 and 6, respectively) for the full profile. Relative intensities, FWHM, and shifts are reported for the [O\textsc{iii}]λ5007 blueshifted components (Cols. 7–9) and for the narrow components (Cols. 10–12) of each quasar. It is difficult to distinguish the relative contribution of the two components in the majority of the cases. One of the main reasons for this is that in many sources the full [O\textsc{iii}]λ5007 emission is shifted to the
blue, implying a shift of [O III]5007 NC with respect to the rest-frame. Some sources like SDSSJ135831.78+050522.8 and SDSSJ161458.33+144836.9 present a NC strongly shifted to the blue, reaching shifts of \(\pm 530 \) and \(-670 \text{ km}\cdot\text{s}^{-1}\) respectively, comparable to the shifts found for the semi-broad component (see e.g. Figs. A.10 and A.15). This is consistent with outflowing gas dominating the [O III]5007 luminosity in luminous quasars (Shen & Ho 2014; Bischetti et al. 2017; Zakamska et al. 2016).

The remarkable feature of the [O III]\lambda4959,5007 profiles is a very intense and blueshifted SBC, such as the one of SDSSJ135831.78+050522.8 (Fig. A.10), which presents a blueshifted SBC that accounts for the full [O III]5007 profile with a \(\text{FWHM} \approx 5422 \text{ km}\cdot\text{s}^{-1}\) and a shift of \(\approx 2080 \text{ km}\cdot\text{s}^{-1}\). In this case, the blueshifted SBC corresponds to 90\% of the full profile and can be interpreted as a strong indicative of outflowing gas. SDSSJ135831.78+050522.8, along with Q1410+096 (Fig. A.11), which shows a very similar profile, requires a strong and broad [O III]5007 to account for the flux on the red side of H\(\beta\). In our high luminosity sample, for 15/22 objects (\approx 70\%) the blueshifted SBC accounts for more than 50\% of the total intensity of the [O III] profile. In fact, in six of these sources, the [O III] consists of exclusively a blueshifted SBC.

Very small blueshifted components are found in low-redshift [O III]\lambda4959,5007 profiles of Pop. B AGN (Zamfir et al. 2008; Sulentic et al. 2004) and even in Population A, shifts at peak above 250 km\cdot s^{-1} are very rare (the so-called ‘blue-outliers’: Zamanov et al. 2002). At high-redshift, Pop. B [O III]5007 profiles do present significant blueshift SBC components but they still present different properties when compared to Pop. A sources: in our sample, the full profiles of Pop. A present a [O III] \(\text{FWHM} \approx 2000 \text{ km}\cdot\text{s}^{-1}\) while Pop. B profiles have \(\text{FWHM} \approx 1450 \text{ km}\cdot\text{s}^{-1}\). The more remarkable difference is seen in the shifts at 9/10 and 1/2 intensities of the full profile (\(c_1(1/2) = -850 \text{ km}\cdot\text{s}^{-1}\) for Pop. A and \(-480 \text{ km}\cdot\text{s}^{-1}\) for Pop. B). However, the A.I. of the two populations are almost the same, indicating that the lines present similar profile shapes. The [O III]\lambda4959,5007 emission of both Pop. A and Pop. B appears to be strongly affected (if not dominated) by outflowing gas.

An important consequence for redshift estimates is that the [O III]5007 lines should be avoided when considering high-z quasars. In addition, three Pop. A (SDSSJ210524.49+000407.3, SDSSJ210831.56-063022.5, and SDSSJ235808.54+012507.2) and three Pop. B sources ([HHB9]0029+073, CTQ408, and SDSSJ153380.55+085517.0) present [O III]5007 full profiles that can be well represented only by the blueshifted component (see the respective spectra in Figs. A.22, A.2.3, A.3, and A.14).

Figure 5 shows the relation between \(W([\text{O III}])\) and \(|c(9/10)|\) of [O III]5007. For our sample, the \(W([\text{O III}])\) ranges from \(\approx 50 \text{ Å}\) for some Pop. B sources to \(\approx 1\) Å for XAs, reaching the detection limit. It shares the same location as the high-redshift HE data. No clear difference between the location of Pop. A and Pop. B is confirmed by the median values of equivalent widths, 12 Å vs 10 Å for Pop. A and B, respectively (the average \(W\) is affected by the two A3 extremely faint sources with \(|W([\text{O III}])| \leq 1\) Å). At low \(z\) (and low luminosity), sources have considerably larger \(W\) values but lower velocity centroids than the high-z sample. Our sample is located at the low end of the [W (O III)] distribution of low-\(z\) sources as expected for luminous quasars (Shen & Ho 2014), and in a shift range that at low \(z\) is the exclusive domain of the rare, namesake ‘blue outliers’ (Marziani et al. 2016b). Figure 5 also shows that the radio-loud quasars from our sample are very tightly grouped together with moderate blueshifts for high-\(L\) quasars (\(\leq 500 \text{ km}\cdot\text{s}^{-1}\) at 0.9 fractional intensity).

A comparison between \(c_1(1/2)\) and \(\text{FWHM}\) of the [O III]5007 profiles is shown in Fig. 6. There is a strong...
correlation between the blueshift of \([\text{O III}]\) and its centroid at 1/2 intensity, and the FWHM. The dashed line in the plot traces the linear regression between both parameters, derived from an unweighted least squares fit:

\[
c(1/2)_{[\text{O III}]} \approx (-0.65 \pm 0.08) \text{FWHM}([\text{O III}]) + (530 \pm 205).
\]  
(1)

Table 7 lists this linear relation, along with the other that relates to \(\text{C IV}\, \lambda 1549\). We report the fitted parameters (Cols. 1 and 2), the method used (Col. 3), the linear correlation coefficients (Cols. 4 and 5), the rms (Col. 6), the Pearson \(r\) score (Col. 7), and its associated null hypothesis probability value (Col. 8). Equation (1) confirms several previous works (Komossa et al. 2008; Marziani et al. 2016a) and justifies the interpretation of the \([\text{O III}]\, \lambda 5007\) profile in terms of a blueshifted semibroad component and of a narrow component (Zhang et al. 2011).

5.3. UV

The fits for the UV emission lines are shown in Appendix A, along with the full UV spectra of the 15 available sources (10 Pop. A and 5 Pop. B). Spectrophotometric measurements in the UV region are reported in Table 8 and concern the 1900 Å blend, \(\text{C IV}\, \lambda 1549+\text{He II}\, \lambda 1640\), as well as flux intensity and equivalent width of Si IV+O IV (Cols. 3–4), C IV (Cols. 5–6), He II (Cols. 7–8), Al III (Cols. 9–10), C III] (Cols. 11–12), and Si III (Cols. 13–14).

5.3.1. 1900 Å blend

Table 9 presents the measurements resulting from the specfit analysis of the 1900 Å blend. Intensities, FWHM, and shifts are shown for the emission line profiles and their components, whenever the profile presents more than just one component.

In Cols. 2–4, we list the relative intensity, FWHM, and shift of the blueshifted component of Al III\,\lambda 1860; Cols. 5–7 show the broad component of Al III\,\lambda 1860; Cols. 8–10 for Si III\,\lambda 1892.

The Al III\,\lambda 1860 contribution can be well fitted assuming only a BC for all Pop. A sources but four: SDSSJ005700.18+143737.7, SDSSJ1210524.49+000407.3, SDSSJ120831.56–063022.5, and SDSSJ132012.33+142037.1. These three sources are the ones that are located in the A3 region of the quasar MS. In these cases, we need to add a BLUE component with 3000 \(\leq\) FWHM \(\leq\) 4500 km s\(^{-1}\) in the Al III\,\lambda 1860 doublet and in the Si III\,\lambda 1892 emission line profile. We have imposed the same FWHM for both components.

The Pop. A C III]\,\lambda 1909 profile can be well reproduced by a strong BC at rest-frame in combination with a component that accounts for the Fe III\,\lambda 1914 contributions in its red wing. The motivation to include the Fe III\,\lambda 1914 line resides in the selective enhancement due to Lyman \(\alpha\) fluorescence that is well-known to affect the UV Fe II emission and Fe III emission as well (Sigut & Pradhan 1998; Sigut et al. 2004). Of the Fe II features the UV multiplet 191 at \(\lambda 1785\) is known to be enhanced by Ly\(\alpha\) fluorescence: a strong Fe II \(\lambda 1914\) emission line component.

For Pop. B sources, Al III\,\lambda 1860 and Si III\,\lambda 1892 are well represented by only one component and in the five cases these emission lines share the same FWHM and are centred at the respective rest-frame wavelength. However, the C III]\,\lambda 1909 VBC is systematically less broad than the H\(\beta\) VBC; average FWHM is \(\approx 7000\) km s\(^{-1}\) for C III]\ versus \(\approx 12\,000\) km s\(^{-1}\) for H\(\beta\).

5.3.2. \(\text{C IV}\, \lambda 1549+\text{He II}\, \lambda 1640\)

Measurements related to the \(\text{C IV}\, \lambda 1549+\text{He II}\, \lambda 1640\) blend are reported in Table 10. As for H\(\beta\), we list FWHM (Col. 2), A.I. (Col. 3), kurtosis (Col. 4), and centroids \(c(1/4)\), \(c(1/2)\), \(c(3/4)\) and \(c(9/10)\) in Cols. 5–8 for the \(\text{C IV}\, \lambda 1549\) full line profile. Information on individual components is also given for both \(\text{C IV}\, \lambda 1549\) and He II\,\lambda 1640. Columns 9–11 give the
In general, the BLUE component accounts for at least 50% of the C IV1549 full profile, but still a fraction that is lower than in Pop. A (∼70%). Correspondingly, the Pop. A C IV1549 profiles in general present higher blueshifts and asymmetry indices than the ones measured in Pop. B.

The top and bottom panels from Fig. 7 show the relation between the rest-frame equivalent widths of C IV1549 and the centroid velocities at 1/2 peak intensity (c(1/2) and FWHM respectively). We also include in the figure the bright, high-z α sample of Martinez-Aldama et al. (2018) as well as the high-z data from S17 and the FOS low-z data from S07. Our data are in good agreement with the ones of Martinez-Aldama et al. (2018) and S17. Our sample, together with the high-L comparison samples, presents smaller values of C IV1549 equivalent width when compared with the FOS data. Additionally, the high-z, high-L sources are those that present the most blueshifted C IV1549 profiles among all quasars (Shen et al. 2011; Rankine et al. 2020; Vietri et al. 2018, 2020). The Pearson correlation coefficient between W and c(1/2) of C IV1549 for the Pop. A sources is −0.64 (with ρ = 2.1 × 10−12) and their relation is given in Table 7. There is also a correlation between W and FWHM C IV1549 with r ≈ −0.49, if we restrict the samples to only Pop. A objects (Table 7).

Figure 8 presents the strong correlation between FWHM and c(1/2) of the C IV line, with a Pearson r ≈ −0.90 for high-z Pop. A sources:

\[
\text{c(1/2)_{CIV}} = (-0.68 \pm 0.10) \times \text{FWHM(C IV)} + (2000 \pm 737).
\]
Table 9. Measurements on the 1900 Å blend.

| Source                      | λ1900 (km s⁻¹) | λ3268 (km s⁻¹) | λ3268 (km s⁻¹) | λ4999 (km s⁻¹) | λ5105 (km s⁻¹) | λ5349 (km s⁻¹) | λ5480 (km s⁻¹) | λ5760 (km s⁻¹) | λ5876 (km s⁻¹) | λ6300 (km s⁻¹) | λ4959 (km s⁻¹) | λ4959 (km s⁻¹) |
|-----------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Population A               |                |                |                |                |                |                |                |                |                |                |                |                |
| SDSSJ153830.55+112943.4      | 0.0            | 1.00           | 0.0            | 100.00         | 0                | 0.0            | 0.0            | 1.00           | 0.0            | 1.00           | 0.0            | 1.00           |
| SDSSJ153830.55+112943.4      | 0.0            | 1.00           | 0.0            | 100.00         | 0.0             | 0.0            | 0.0            | 1.00           | 0.0            | 1.00           | 0.0            | 1.00           |
| SDSSJ153830.55+112943.4      | 0.0            | 1.00           | 0.0            | 100.00         | 0.0             | 0.0            | 0.0            | 1.00           | 0.0            | 1.00           | 0.0            | 1.00           |
| Median                      | 0.0            | 1.00           | 0.0            | 100.00         | 0.0             | 0.0            | 0.0            | 1.00           | 0.0            | 1.00           | 0.0            | 1.00           |

Notes. (a) UV line profiles of this source were fitted with Lorentzian shapes. See note in the Appendix A (Fig. A.14).
Table 10. Measurements on the CIV1549+HeII1640 full line profiles and SPECFIT analysis.

| Source | FWHM | A1 | A2 | A3 | A4 | A5 | A6 | A7 | A8 | A9 | A10 | A11 | A12 | A13 | A14 | A15 | A16 | A17 | A18 | A19 | A20 | A21 | A22 | A23 | A24 | A25 | A26 |
|--------|------|----|----|----|----|----|----|----|----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|         | (km s<sup>-1</sup>) |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| Population A | |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| SDSSJ005700.19+343747.7 | 604.8 ± 154.2 | 0.18 ± 0.59 | 0.49 ± 0.02 | 2049.5 ± 1015.0 | 2093.4 ± 1026.1 | 1001.9 ± 1006.1 | 418.1 ± 413.9 | 480.0 ± 481.6 | 1000.8 ± 1006.1 | 1002.2 ± 1006.1 | 1001.0 ± 1006.1 | 1001.0 ± 1006.1 | 1001.0 ± 1006.1 | 1001.0 ± 1006.1 | 1001.0 ± 1006.1 | 1001.0 ± 1006.1 | 1001.0 ± 1006.1 | 1001.0 ± 1006.1 | 1001.0 ± 1006.1 | 1001.0 ± 1006.1 | 1001.0 ± 1006.1 | 1001.0 ± 1006.1 | 1001.0 ± 1006.1 | 1001.0 ± 1006.1 | 1001.0 ± 1006.1 | 1001.0 ± 1006.1 | 1001.0 ± 1006.1 |

A. Deconto-Machado et al.: High-redshift quasars along the main sequence
Fig. 7. Comparison between different properties of the C IV emission line profile. Top: relation between centroid velocity at 1/2 intensity (c(1/2)) and rest-frame equivalent width of C IV. Bottom: FWHM of C IV versus W(C IV). Colour scheme for our sample is the same as in Fig. 4. Filled magenta squares indicate data from Martínez-Aldama et al. (2018). Blue and red open squares represent Pop. A and Pop. B sources from our sample and the colour scheme is the same as in Fig. 4. Low-z FOS data from S07 are represented by grey (Pop. A) and orange (Pop. B) squares. Green point-dashed lines indicate the linear regression obtained through the bisector method including only the Pop. A sources from the four samples. Error bars refer to 1σ level of confidence and were estimated only for our sample.

This relation is in good agreement with previous results (e.g. Coatman et al. 2016; Marziani et al. 2016b; Sulentic et al. 2017; Sun et al. 2018; Vietri et al. 2018, and references therein). As the blueshift of C IV increases, FWHM(C IV) is likely to increase as well. Both C IV FWHM and blueshift parameterised by c(1/2) show a clear increase from spectral types A1 to A3, the latter being those with the highest blueshifts (median value ≈4500 km s$^{-1}$) and the widest FWHM (median ≈9000 km s$^{-1}$).

In the case of C IV in Pop. B sources, the shifts at 1/2 flux intensities are also displaced towards blue wavelengths with average value of c(1/2) ≈ −1681 km s$^{-1}$ and mean FWHM ≈ 5940 km s$^{-1}$, somewhat smaller than for Pop. A. However, the c(1/2) values for the Pop. B sources from our sample are still higher than the majority of the low-luminosity and low-redshift quasars, which usually present a c(1/2) ≲ 200 km s$^{-1}$. Low-luminosity Pop. B spectra show a sort of dichotomy in the C IV shift distribution: a fraction of sources remains unshifted or with modest shifts to the blue (the orange and grey “cloud” of points in Fig. 8). The FOS low-luminosity and low-redshift sources tend to present smaller c(1/2) in the C IV emission line when compared with our data. This indicates that the C IV blueshifted components seen in higher-luminosity sources are more prominent than the ones observed in quasars of lower luminosities.

5.3.3. Si IV$1397+O IV$$1402$

Table 11 presents the measurements on the full profiles of Si IV$1397+O IV$$1402$. We report values of FWHM (Col. 2), A.I. (Col. 3), kurtosis (Col. 4), c(1/2) (Col. 5), and c(9/10) (Col. 6). Si IV$1397+O IV$$1402$ BC is set at rest-frame and our initial guess for this component takes into account the results obtained for the C IV$_{BC}$ after fitting the C IV$1549+He II$$1640$ region. SDSSJ141546.24+112934.3 has very strong and wide absorption lines in this region of the UV spectra, which makes it difficult to perform a reliable fitting (see Fig. A.12).

Regarding the BLUE of Si IV$1397+O IV$$1402$, they are very wide (even if they are apparently not as wide as in C IV$1549+He II$$1640$), reaching more than 6000 km s$^{-1}$ in all cases, and representing a significant percentage of the full emission line profile. The shifts towards shorter wavelength are also smaller than for C IV$1549$, but they are still very high, going from 800 to 2700 km s$^{-1}$, with the extreme amplitude of SDSSJ141546.24+112934.3 that reaches ≈4400 km s$^{-1}$.

The fluxes of C IV$1549$ and Si IV$1397$ presented in Table 8 indicate that on average Pop. A presents higher values of the C IV$1549$/Si IV$1397$ ratio (>0.69) than Pop. B (<0.49). This discrepancy may be linked to differences in chemical abundances with Pop. A sources being systematically more metal
rich (cf. Śniegowska et al. 2021; Punsly et al. 2020). However, the issue goes beyond the scope of the present work and will be discussed elsewhere.

6. Discussion

In the previous section, we show that Pop. A and Pop. B sources may reflect different contributions of line emitting gas that produces prominent blueshifted features and is most likely associated with an outflow. To shed further light on the role of outflows, we now report an interline comparison in both the optical and UV spectral regions. We highlight the effect of the outflowing components on the estimate of physical parameters such as black hole mass and Eddington ratio.

6.1. Defining the outflow

6.1.1. Hβ and [O III]λλ4959,5007

The relation between the FWHM of the full profiles of Hβ and O III]λ5007 is shown in Fig. 9. In general, the two populations present a FWHM[Hβ(out)] higher than FWHM(O III]λ5007), as expected from previous observations (Sulentic et al. 2004, 2007; Zamfir et al. 2010; M09). At low-z, only in the case of the ‘blue-outliers’ the [O III]λλ4959,5007 profiles appear to be very boxy-shaped and with the FWHM > 1000 km s\(^{-1}\). Some of these sources are NLSy1s and the [O III]λλ4959,5007 FWHM is becoming comparable to the one of the broad Hβ profiles (Zamanov et al. 2002; Komossa et al. 2008, 2018; Cracco et al. 2016; Bertoni & Järvelä 2021). At high z and high luminosity the [O III]λλ4959,5007 profiles often appear much broader, as do also the Hβ broad profiles (Carniani et al. 2015; Fiore et al. 2017; Villar Martín et al. 2020). Two cases in point, taken from previous works, are 2QZJ002830.4–281706 at z = 2. (Cano-Díaz et al. 2012; Carniani et al. 2015) and HE 0940–1050 at z = 3.1 (Marziani et al. 2017a). We have four sources that present [O III]λλ4959,5007 FWHM above 3000 km s\(^{-1}\), comparable to the Hβ FWHM, with one extraordinary case in which FWHM(Hβ(out)) is smaller than FWHM(O III]λ5007). (SDSSJ135831.78+050522.8, Pop. A1), with FWHM(Hβ(out)) ≈ 3550 km s\(^{-1}\) and FWHM([O III]λ5007) ≈ 4320 km s\(^{-1}\) (see Fig. A.10). Although FWHM of [O III]λλ4959,5007 >2000 km s\(^{-1}\) are frequently observed at high luminosity, some extreme values should be taken with care because the [O III]λλ4959,5007 profiles are weak and broad: it is difficult to properly define the [O III]λλ4959,5007 profiles especially when the broad Hβ red wing is strong.

6.1.2. [O II]λλ3727 vs. C IV λλ1549

Figure 10 shows the relation between c(1/2) for [O III]λλ4959,5007 and C IV λλ1549. The HE comparison sample analysed in M09 and S17 is included. The sources that present strong shifts in the [O III]λλ4959,5007 emission line profiles will also present it in C IV λλ1549, in agreement with the HE data. Both lines show a correlation between their widths and shifts (Fig. 6 for [O III]λλ4959,5007 and Fig. 8 for C IV λλ1549) indicating that the broadening is mainly associated with a blueshifted component that is increasing in prominence with increasing shift. The least-squares linear regression of Fig. 10 (considering both HEMs and our sample) is given by:

\[
c(1/2)_{C IV} = (1.50 \pm 0.31) c(1/2)_{O III} + (-1239 \pm 276) \quad (3)
\]

in a good agreement with the study of Coatman et al. (2019). The trend (actually, a weak, marginally significant correlation at a 3σ confidence level) of Fig. 10 raises the issue of the relation between [O III]λλ4959,5007 and C IV λλ1549 outflows. There is evidence suggesting that the semi-broad component of [O III]λλ4959,5007 W remains almost constant with luminosity (Marziani et al. 2016a, Sect. 4.3), overwhelming the narrow, core component. The narrow component is however mainly associated with the NLR that may extend up to tens of kpc (Bennert et al. 2002, 2006). The dispersion in the relation with more sources around 0 shift in [O III]λλ4959,5007 might
be explained by a narrow component whose strength may depend on the past AGN evolution (Storchi-Bergmann et al. 2018). It is therefore not surprising that, even if a large C IV1549 shift is measured, the [O III]λ4959,5007 profile may be unshifted or show only a modest blueshift. However, the presence of a shift correlation and the relatively large [O III]λ4959,5007/C IV1549 FWHM ratio support a physical connection between an inner outflow on scales of a few hundreds gravitational radii where the BLUE C IV1549 component is emitted, and an outflow at the outer edge of the BLR, beyond 10⁻¹⁰⁻¹⁰ gravitational radii (Zamanov et al. 2002), where the [O III]λ4959,5007 semibroad component likely originates. The nature of this connection remains unclear. It is beyond the scope of the present paper and might be investigated elsewhere.

6.1.3. C IV1549 versus Hβ

The top panel of Fig. 11 represents the relation between FWHM(HβBC) and FWHM(C IVfull), including the S17 sample. Our data is in agreement with this comparison sample in terms of a clear A-B separation. The Pop. A sources seem to present a trend from A1 to A3 in the FWHM(C IVfull) where the A3 sources show the largest values. The FWHM(C IVfull) is larger than the FWHM(HβBC), and the widths of the two lines are not correlated. There is a degeneracy between C IV1549 and Hβ: to a single value of Hβ FWHM corresponds a wide range of C IV1549 FWHM (cf. S07; Capellupo et al. 2015; Mejía-Restrepo et al. 2016; Coatman et al. 2017). The systematically broader profile can be interpreted as a consequence of the dominance of the outflow component in the C IV1549 line profile (Marziani et al. 2019).

The bottom panel of Fig. 11 shows the FWHM(C IVfull) vs. FWHM(HβBC) where, apart from including S17 data, we also display the low-z sample from S07 for comparison. In this plot, the separation between Pop. A and Pop. B is even clearer: Pop. A sources show broader C IV1549, while those of Pop. B have values consistent with, or narrower, than Hβ.

6.1.4. C IV1549 versus Al III1860

Figure 12 shows FWHM of the full profiles of C IV1549 versus FWHM of Al III1860. The FWHM(C IVfull) presents significantly higher values than FWHM(Al III). This indicates that the relation between C IV1549 and Al III1860 is similar to the one of C IV1549 and Hβ. In both cases, the C IV1549 FWHM tends to be larger: in particular, always significantly so for Pop. A and larger or consistent for Pop. B. The cyan and magenta dashed lines connect the FWHM estimated from the Al III1860 BC with and without a BLUE component: without the BLUE (stars), the Al III1860 FWHM becomes closer to, but remains significantly smaller than the FWHM of the C IV1549 full profile.

6.2. Virial black hole mass estimates

A comparison between the FWHM of Al III1860 and Hβ (BC and full) profiles is shown in Fig. 13. The figure includes the data from Marziani et al. (2022b, hereafter M22) that involve exclusively Pop. A sources. The FWHM of HβBC is consistent with the FWHM of Al III1860 for Pop. A: their average ratio (FWHM Al III over FWHM Hβ) in our sample is ≈0.87 ± 0.18. The right panel of Fig. 13 shows a comparison between FWHM(Al III) vs. FWHM of full Hβ. The purple dotted vertical line indicates the A/B boundary as in Fig. 3. The location of our Pop. A objects remains in agreement with the results from M22, and with those for HβBC. There is a clear deviation from the 1:1 line in the location of Pop. B sources: for the 5 Population B sources of our sample the average ratio is just 0.57 ± 0.12 (cf. Marziani et al. 2017b). These results provide evidence that Pop. B Al III1860 is systematically narrower than Hβ full profile, most likely because of the strong VBC contribution. The ratio FWHM Al III1860 over HβBC is in fair agreement ≈0.79 ± 0.16 for Pop. B, and therefore the Hβ VBC should not be included on the black hole mass estimation. The 20% difference between the FWHM HβBC
and FWHM AlIII 1860 for Pop. B sources is marginally significant and should be confirmed by larger samples.

The black hole masses are estimated through different scaling relations using emission lines such as those based on the FWHM of Hβ, AlIII 1860, and CIV 1549. The scaling law of Vestergaard & Peterson (2006, hereafter VP06) was used to estimate the mass $M_{BH}$ with FWHM Hβ. We used Eq. (18) from Marziani et al. (2019, $\sigma = 0.33$) to estimate $M_{BH}$ with the CIV 1549 FWHM. The left panel of Fig. 14 presents a comparison between the $M_{BH}$ estimates using the scaling law for CIV 1549 from Marziani et al. (2019) and the Hβ scaling law of Vestergaard & Peterson (2006). The open squares in this plot indicate the data from Marziani et al. (2019), which include high- and low-z sources. Our sample agrees with the previous estimates and corresponds to the extreme cases, with the largest $M_{BH}$ reaching $10^{10} M_\odot$.

The plot of $M_{BH, AlIII}$ vs. $M_{BH,Hβ}$ (right panel of Fig. 14) relies on the $M_{BH}$ scaling law from M22. The $M_{BH,Hβ}$ and $M_{BH, AlIII}$ values obtained for our sources are compatible within the confidence interval of the M22 scaling law for AlIII 1860. We caution that the relation given in this equation has been derived for Pop. A sources and, consequently, it may lead to larger uncertainties for Pop. B quasars. For these sources we apply a correction $\xi = \text{FWHM}_{H\beta, BC}/\text{FWHM}_{AlIII} = 1.35 \pm 0.10$ to the FWHM(Al III), (Marziani et al. 2017a, who assumed FWHM Hβ as the reference virial broadening estimator).

The equations that describe the relations between $M_{BH}$ estimations using $\xi$-corrected CIV 1549 and AlIII 1860 are listed in Table 12. Column 1 lists the method used for the linear regression (orthogonal and bisector); Cols. 2 and 3 present the linear and angular coefficients, along with the respective standard deviations; rms error and Pearson correlation coefficient $r$ are reported in Cols. 4 and 5, respectively.

The original CIV 1549 VP06 relation lacks a correction because of the bias introduced by non-virial broadening (i.e. by the blueshifted component; Brotherton et al. 2015;
Table 12. Linear relations between the different $M_{\text{BH}}$ estimates using orthogonal and bisector methods.

| Method       | a ± da | b ± db | rms   | CC  |
|--------------|--------|--------|-------|-----|
| Orthogonal   | $-0.495 ± 0.306$ | $1.053 ± 0.034$ | 0.315 | 0.949 |
| Bisector     | $-0.471 ± 0.289$ | $1.050 ± 0.032$ |       |      |

$M_{\text{BH},\text{CD},\text{M19}} = a + b \cdot M_{\text{BH},\text{VP06}}$

$M_{\text{BH},\text{ALM},\text{M22}} = a + b \cdot M_{\text{BH},\text{VP06}}$

Table 13. Weighted averaged masses, luminosity at 5100 Å, and Eddington ratio ($L/L_{\text{Edd}}$), in logarithmic scale.

| Source       | $M_{\text{BH},\text{Dj}}$   | $M_{\text{BH},\text{II}}$ | $L_{5100}$ | $L_{1549}$ | $L/L_{\text{Edd}}$ |
|--------------|-----------------|-----------------|-----------|-----------|------------------|
| Population A | $9.39 ± 1.41$   | $9.37 ± 0.27$   | $46.65 ± 5.60$ | $46.41 ± 5.57$ | $0.10 ± 0.01$   |
| Population B | $9.71 ± 1.46$   | $9.68 ± 5.62$   | $46.81 ± 5.62$ | $0.07 ± 0.01$ |                   |

Notes. (a) We use $L_{5100}$ and $L_{1549}$ with the 1900 Å blend regions were not fitted in these cases.
(b) We compute the weighted averaged mass between the $H_{\beta}$ and Al II(1860) estimates only. (c) We compute the weighted averaged mass between the $H_{\beta}$ and C IV1549 estimates only.

6.3. Dependence on accretion parameters

6.3.1. $[\text{O\textsc{iii}}] \lambda 4959,5007$

Figure 15 shows the dependence of $W([\text{O\textsc{iii}}] \lambda 4959,5007)$ on $H_{\beta}$ and $L/L_{\text{Edd}}$. Our sample presents $W([\text{O\textsc{iii}}] < 25 \text{ Å}$ in the majority of the cases, with only two outliers (SDSSJ141546.24+112943.4 with $\approx 34 \text{ Å}$ and H0055–2659 with $\approx 41 \text{ Å}$). The $W([\text{O\textsc{iii}}])$ of our sample is relatively small when compared with low-$z$ sources. However, our data more frequently show blueshifts in $c(9/10)$.

The right panels of Fig. 15 consider only sources that present $c(9/10) < -250 \text{ km s}^{-1}$. In this case, all the sources fit within $W([\text{O\textsc{iii}}]) < 25 \text{ Å}$ and are found in a wide range of $M_{\text{BH}}$ as for the distribution of the full samples. Sources with $c(9/10) < -250 \text{ km s}^{-1}$ have an average Eddington ratio of $< 0.09$: at high Eddington ratios, the $[\text{O\textsc{iii}}] \lambda 4959,5007$ profiles tend to be strongly affected or dominated by the blueshifted SBC. In addition, the $[\text{O\textsc{iii}}] \lambda 4959,5007$ W remains roughly constant over a wide range of masses and luminosity, indicating that the luminosity of the blueshifted SBC is proportional to the continuum luminosity. This result provides evidence that the outflow traced by the blueshifted $[\text{O\textsc{iii}}] \lambda 4959,5007$ is directly related to the active nucleus, as proportionality between line and continuum luminosity is a classical proof of photoionisation (Osterbrock & Shuder 1982).

6.3.2. C IV1549

In Fig. 16, we provide an analysis of the dependence of C IV1549 shift measured by $c(1/2)$ on luminosity and $L/L_{\text{Edd}}$. We include the data analysed by Marziani et al. (2019), along with the present sample data. The same trend appears to be followed by both ours and Marziani et al. (2019) samples. Sources that present the largest values of C IV1549 $c(1/2)$ are Population A, with two $x$-axes (SDSSJ210524.47+000407.3 and SDSSJ210831.56–063022.5), reaching $c(1/2) \approx 5000 \text{ km s}^{-1}$.

As in S17, the left plot of Fig. 16 indicate a clear relation (with a Pearson correlation coefficient of 0.59) between $c(1/2)$ of C IV1549 and $L/L_{\text{Edd}}$, given by the following equation for the absolute value of the centroid shift at 1/2:

$$\log c(1/2)_{\text{CIV}} = (0.43 \pm 0.06) \log L/L_{\text{Edd}} + (3.25 \pm 0.04).$$

A similar relation can also be derived between the absolute value of C IV1549 $c(1/2)$ and $L_{\text{bol}}$ at 1540 Å (right panel of Fig. 16):

$$\log c(1/2)_{\text{CIV}} = (0.18 \pm 0.03) \log L_{\text{bol}} + (-5.70 \pm 1.46).$$

The Pearson correlation coefficient in this case is 0.54. These relations are consistent with those of S17 who found slope $\approx 0.5$ and $\approx 0.2$ for the dependence on Eddington ratio and luminosity, respectively. Since the S17 data were included in the linear regression, we can say that the new data confirm the slope difference that suggests a major role of the $L/L_{\text{Edd}}$ for governing the shift amplitude and a secondary effect of luminosity.

6.4. Redefining optical properties of high-$z$ sources

Figure 17 shows the relation between the Eddington ratio and the bolometric luminosity. The distinction between Pop. A and
Pop. B is very clear in both low- and high-redshift samples including our sample as well as the data analysed by S07 and S17. The systematically higher Eddington ratio of the high-luminosity samples may be in part the result of a Malmquist type bias (Sulentic et al. 2014) on the assumption of a constant bolometric correction over a wide range in luminosity, orientation effects, and intrinsic evolution of the Eddington ratio (e.g. Cavalliere & Vittorini 2000; Volonteri et al. 2003; Shankar et al. 2009). For instance, the radio-loud sources from our sample seem to be the more extreme cases of their respective population, reaching \( L/ L_{\text{Edd}} \approx 1 \). They are core-dominated and presumably beamed in the direction of the observer. The line profiles appear composite, in the sense that they show a narrower core superimposed on a VBC. The width of the narrower core may be lowered if the emitting regions are constrained within a flattened geometry that is seen pole-on. This effect blurs the distinction between Pop. A and B, letting sources that are intrinsically Pop. B enter into the domain of Pop. A in the MS optical plane, which may indicate that the converse Pop. A sources have more similar values at low and high luminosity sources (S07; M09; S17, together with our sample). The Eddington ratio is consistently higher in Pop. A sources rather than in Pop. B sources for both cases of luminosity and redshift separation. Low-redshift, low-luminosity sources present very small \( L/ L_{\text{Edd}} \) values for Pop. B. The more extreme case is for low-redshift Pop. B1++, with a \( L/ L_{\text{Edd}} \approx −1.65 \). On the contrary, Pop. A sources have more similar values at low and high luminosity. There is no notable difference between high and low-luminosity and high and low-redshift distribution on the spectral type and log \( L/ L_{\text{Edd}} \) plane, which may indicate that the more luminous sources present the highest Eddington ratios because of a Malmquist-type bias (Sulentic et al. 2014) rather than evolutionary effects on \( L/ L_{\text{Edd}} \).

Of the four quasars that are radio-loud, B1422+231, PKS 1937–101, and PKS 2000–330 are classified as Pop. A, while PKS 2126–15 is a Pop. B source. From four sources we can only make some preliminary considerations that will be properly discussed in a companion paper involving mainly radio-loud objects. The basic result is that the four RLs do not have outstanding properties with respect to the RQ samples considered in this paper. They share the trends between Hβ and [O III]λλ4959,5007 RQ profile parameters. A remarkable aspect
is that the four RL AGN studied in this paper show high Eddington ratio, a fact that is never observed in powerful RL sources at low-$z$ (Sikora et al. 2007; Zamfir et al. 2008) that are more frequently classified as population B sources. At low-$z$, low-power, ’jetted’ sources for which high Eddington ratio has been estimated to be $\sim 1$ are known to exist (the so-called RL NLSy1s; Komossa et al. 2006; Berton et al. 2015; Foschini et al. 2015). Even if $L/L_{\text{Edd}}$ might be overestimated, the implication is that there is apparently no empirical inconsistency between powerful jetted emission and high accretion rate.

7. Conclusions

We presented a sample of 22 high-redshift and high-luminosity quasars (12 Pop. A; 10 Pop. B) observed with the VLT/ISAAC spectrograph to cover the H$\beta$ spectral range shifted into the near infrared. A dedicated analysis has been performed on the most prominent emission features in the new optical spectra (H$\beta$, [O III]$\lambda\lambda 4959,5007$, Fe II), as well as in survey or published UV spectra (Al III]$\lambda 1860$, C III]$\lambda 1909$, C IV]$\lambda 1549$, Si IV]$\lambda 1397$, Fe II, Fe III]$\lambda 1914$) to measure several parameters related to the emitting gas physical conditions and dynamics. Our main conclusions are as follows.

1. We confirm that the full profile of H$\beta$ may be generally well represented by solely a Lorentzian BC for Pop. A quasars, while two Gaussians (BC and VBC) provide a satisfactory fit for those of Pop. B, with the broader, redshifted VBC accounting for $\sim 50\%$ of the emission line. Also, some Pop. A H$\beta$ profiles from our sample present outflowing components that seem to be related to those observed in the [O III]$\lambda\lambda 4959,5007$ lines.

2. Compared to low-$z$ and low-luminosity samples, our data presents a displacement in the MS in the direction of higher values of FWHM of the H$\beta$ full profile and $R_{\text{Edd}}$. The relation between profile parameters and the $M_{\text{BH}}$ and $L/L_{\text{Edd}}$ differences between Pop. A and B are also confirmed, in the form seen in previous high-luminosity samples.

3. The [O III]$\lambda\lambda 4959,5007$ profile is broad and not reproducible with a simple Gaussian. All [O III]$\lambda\lambda 4959,5007$ profiles of our sample are blueshifted by more than 250 km $\text{s}^{-1}$. Differently from the low-$z$ range, high-$z$ Pop. B [O III]$\lambda\lambda 4959,5007$ profiles present significant contribution of blueshifted semi-broad components, even though they are still less strong than the ones found in Pop. A sources. Nevertheless, both populations seem to share similar asymmetry indexes, which indicates that their profiles present comparable shapes.

4. In some cases, the [O III]$\lambda\lambda 4959,5007$ FWHM reaches values comparable to those of H$\beta$. This effect is found, in particular, for sources with high $L/L_{\text{Edd}}$, and may be compared with the case of highly-accreting NLSy1s at low $z$. Line widths appear extraordinarily large (thousands km $\text{s}^{-1}$) because of the high black hole mass values involved. [O III]$\lambda\lambda 4959,5007$ correlations between FWHM and shift, and also between W and shift mirror the correlations seen in C IV]$\lambda 1549$.

5. The [O III]$\lambda\lambda 4959,5007$ lines should be avoided for accurate redshift estimates in high-$L$, high-$z$ quasars, as in most of sources the [O III] lines are dominated by a blueshifted SBC and no rest-frame narrow component could be clearly identified. The average shift of the [O III] profile peak is $\sim 250$ km $\text{s}^{-1}$, which may lead to a considerable systematic blueshift of $\beta \sim 0.0017$ on the redshift estimation.

6. Several C IV]$\lambda 1549$ correlations (most notably the one between shift and width) and the C IV]$\lambda 1549$ parameters’ dependence on Eddington ratio and mass (or luminosity) are confirmed (including the ones of S17). Outflow-dominated profiles tend to have lower $W$, larger FWHM, and shifts. The three parameters are definitely related.

7. We exploit the VP06 scaling law as reference for $M_{\text{BH}}$ estimates, and we verified that the scaling law based on Al III]$\lambda 1860$ is a reliable estimator with respect to black hole masses derived from H$\beta$. The C IV]$\lambda 1549$ scaling law requires a FWHM correction.

8. [O III]$\lambda\lambda 4959,5007$ and C IV]$\lambda 1549$ seem to follow a very similar, strong correlation between FWHM and shift, as measured by the $c(1/2)$. The [O III]$\lambda\lambda 4959,5007$ and C IV]$\lambda 1549$ outflow velocities are related, as suggested by the correlation between their shift amplitudes shown in Fig. 10.

9. The radio loud sources in the high-$z$ range seem to be radiating at high values of Eddington ratio (with $L/L_{\text{Edd}} \sim 1$), which is at variance with low-$z$ values, where the most powerful jetted sources belong to Pop. B and radiate at a modest Eddington ratio. The sample studied in this paper is the first part of a sample involving roughly an equal number of RQ and of RI and RL sources. The data in this paper provide a RQ comparison sample for the ISAAC spectra of RL sources that will be presented in a future paper.

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Appendix A: Multicomponent fits in the optical and UV ranges and individual notes

In this appendix, we present the new VLT/ISAAC infrared spectra and the multicomponent fittings for the optical spectral range, including the fits of Hβ+[O III]λ4959,5007. An additional analysis of the UV spectra is also presented for the objects with available UV spectra, from the literature or from SDSS. The UV analysis includes fittings for Si IVλ1397+[O IV]λ1402, C IVλ1549+He IIλ16640 as well as for the 1900 Å blend. We also include notes for some of the individual objects.

A.1. HE 0001-2340

Fig. A.1. HE 0001-2340: (a) Rest-frame spectrum covering the Hβ spectral range obtained with VLT/ISAAC. The spectrum is normalised by the continuum at 5100 Å (the flux values are available at Table 4). The grey dashed line traces a power law that defines the continuum level as obtained with the SPECFIT multicomponent analysis. The green line shows the Fe II contribution. For this object Fe II was fitted only with the red Fe II blend due to the presence of atmospheric absorption in the blue. The vertical dotted lines indicate the rest-frame of the main emission lines in the Hβ spectral range and the grey-shaded area indicate the regions that were not considered in the fittings. The white area indicates the region used to anchor both the continuum and the Fe II template. (b) Result of the fitting after continuum subtraction (upper panel) and the residuals (bottom panel) for the Hβ region. Pink dashed line shows the final fit. Broad Hβ component (BC) is represented by a black line meanwhile red line show the VBC. Orange lines represent narrow components and the blue ones correspond to the blueshifted components. The region in which the Fe II template was fitted is represented by the solid green line. Dotted green line indicate the expected Fe II contribution for the other parts of the spectra.

A.2. [HB89] 0029+073

Jaunsen et al. (1995) listed this source as a gravitational lens candidate. [HB89] 0029+073 is another case in which the Fe II contribution was measured at λ ≥ 5000 Å and then rescaled to obtain the intensity of the Fe IIλ14570 blend.

Fig. A.2. [HB89] 0029+073. Colours and lines as Figure A.1.

A.3. CTQ 0408

As in the case of [HB89] 0029+073, the Fe II of CTQ 0408 was fit on the red side of Hβ with λ ≥ 5000 Å. Radio information about this source was found only in the SUMSS catalogue (Mauch et al. 2003). There is no radio map from NVSS nor FIRST for this object, because it is out of the respective survey fields.
A.4. SDSSJ005700.18+143737.7

Hβ+[O III]λ4959,5007 falls at the red border of the observed spectrum. Consequently, the [O III] measurements should be treated as highly uncertain and special marks have been included in the corresponding tables in the paper. The measurements and the analysis on the [O III] profile were performed with the [O III]λ4959 instead of [O III]λ5007. With respect to the UV spectrum, the object presents strong absorption lines likely associated with intervening absorbers throughout the three UV regions of interest. In the analysis we also included Gaussians profiles for the absorption lines in the fittings. It was necessary to include two blueshifted components for Al IIIλ1860 and Si IIIλ1892, otherwise both Al IIIλ1860 and Si IIIλ1892 BC are shifted by more than 1000 km s⁻¹.

Fig. A.4. SDSSJ005700.18+143737.7. Top panels: Details are the same as in Fig. A.1. (c) Continuum-normalised UV spectrum from SDSS DR-16 with adopted continuum marked in colour. Bottom panels: Fits for (d) Si IVλ1397+O IVλ1402, (e) C IVλ1549+He IIλ1640, and (f) the 1900 Å blend. Pink dashed lines show the final fitting. Broad components are represented by black lines, while blueshifted components are in blue. Green line represents the additional Fe IIIλ1914 line in the red side of C III], observed in extreme Pop. A sources. Brown lines represent the absorptions seen in the spectrum and modelled as negative-flux Gaussians.
A.5. H 0055-2659

The VLT rest-frame optical spectrum of H 0055-2659 presents a very flat profile and small Fe II multiplets contributions.

Fig. A.5. H 0055-2659. Details are the same as in Figure A.1.

A.6. SDSSJ114358.52+052444.9

Fig. A.6. SDSSJ114358.52+052444.9. Top panels: Details are the same as in Fig. A.1 Middle and bottom panels: Same details as in Fig. A.4. Pink dashed lines show the final fitting. Broad components are represented by black lines, while blueshifted components are in blue. Brown lines represent the absorption lines seen in the spectrum.
A.7. SDSSJ115954.33+201921.1

In the optical range, this source presents a very flat spectrum and almost no Fe II contributions.

![Graph showing spectral features](image)

**Fig. A.7.** SDSSJ115954.33+201921.1. Same details as in Figure A.6.
A.8. SDSSJ120147.90+120630.2

This quasar has observations of the Hβ region at the Large Binocular Telescope (LBT), as reported in Bischetti et al. (2017). We stress that their spectrum is very similar to the one of ISAAC/VLT.

Fig. A.8. SDSSJ120147.90+120630.2. Same details as in Figure A.6.
A.9. SDSSJ132012.33+142037.1

Fig. A.9. SDSSJ132012.33+142037.1. Same details as in Figure A.6.
A.10. SDSSJ135831.78+050522.8

Fig. A.10. SDSSJ135831.78+050522.8. Same details as in Figure A.6.
A.11. Q 1410+096

This source has been identified as a BAL quasar by Allen et al. (2011) and the absorption lines are seen in the regions of the Si\textsc{iv}\(\lambda 1397\) and C\textsc{iv}\(\lambda 1549\) emission lines. In order to account for the multiplet contributions in the optical region, we performed a fitting of this Fe\textsc{ii}\(\lambda 4570\) region on the red side of H\textbeta, since the blue part of the Fe\textsc{ii}\(\lambda 4570\) region is close to the border of the spectrum and evidently affected by background subtraction or telluric absorption correction.

For this quasar, we performed the fitting of the C\textsc{iv}\(\lambda 1549\) line based on the He\textsc{ii}\(\lambda 1640\) profile. The Al\textsc{iii}\(\lambda 1860\) BC of 1410+096 is narrow when compared to H\textbeta, which may indicate that H\textbeta might be affected by blueshifted emission. An excess (not included in the fit) is also visible on the blue side of Al\textsc{iii}\(\lambda 1860\) (bottom rightmost panel of Fig. A.11). This source has also been analysed in detail in Deconto-Machado et al. (2022).

Fig. A.11. Q 1410+096. Same details as in Figure A.6.
This object is known as a weak microlensing candidate in the literature (Sluse et al. 2012; Takahashi & Inoue 2014). According to Welling et al. (2014), the quasar is a gravitationally lensed object split into four images separated by \( \sim 1'' \).

SDSSJ141546.24+112943.4 is a modest core-dominated radio-loud source with a logarithmic radio loudness parameter of 1.09.

As can be seen in the UV spectra presented in Fig. A.12, the source is a BAL quasar, with broad absorption lines especially in the C\textsc{iv}\(\lambda 1549\) and Si\textsc{iv}\(\lambda 1397\) regions. Hazard et al. (1984) also report broad absorption lines in Al\textsc{iii}\(\lambda 1860\) that we can see on the blue side of the blend at \( \lambda \approx 1820 \) Å.
A.13. B1422+231

The source was studied in detail for the first time by Patnaik et al. (1992). It consists of a gravitationally lensed system with a diameter of 1.3 arcsec and four non-resolved components from VLA observations. This quasar is lensed into four images by a galaxy with $z = 0.34$ (Tonry 1998). Dadina et al. (2016) used XMM-Newton to study the matter inflow at the centre of this source and found that its X-ray spectrum is quite similar to the one of a typical Seyfert galaxy. Several UV spectra were found in literature (Tonry 1998; Assef et al. 2011; Kundic et al. 1997; O’Dowd et al. 2017), but are not available for public usage or do not correspond to the regions we want to analyze. No SDSS spectrum was found. It has also been analysed in the infrared by Lawrence et al. (1992) who conclude that the source presents similar structures in both radio and infrared. This is one of the radio-loud sources included in our sample.

![Diagram](image.png)

**Fig. A.13.** B1422+231. Colours and lines as the same as in Figure A.1.
A.14. SDSSJ153830.55+085517.0

When compared with the other sources of the sample, this source presents one of the spectra with lowest S/N. The low S/N might be due to the presence of a star that is located very close to the field of the quasar significantly increasing the background of the spectrum. This also may explain why the UV and the optical spectra of SDSSJ153830.55+085517.0 differ so much: while the optical spectrum shows a Pop. B-like profile, the UV is clearly the expected one for a Pop. A3 quasar. If this discrepancy is real, this would be the first case of discordant population classification from the UV and from the optical spectrum. SDSSJ153830.55+085517.0 had the 1900 Å blend fit as Pop. A since it cannot reproduce any Pop. B model and its UV spectrum presents all the characteristics of a Pop. A quasar. SDSSJ153830.55+085517.0 has previous observations in the K-band at LBT (Vietri et al. 2018) and at UKIRT by Dix et al. (2020). In both cases, our NIR spectrum is compatible with those shown for the Hβ region by these authors. As we remarked before, the UV spectrum obtained with BOSS shows a blend at 1900 Å characteristic of the extreme end of Pop. A. An additional old UV SDSS spectrum exists, but it has no information on the 1900 Å blend. A new UV spectrum would be necessary to disentangle its classification and possible peculiarity. Additionally, Bruni et al. (2019) has classified this source as a high-velocity BAL.

![Spectrum Diagram](image)

**Fig. A.14.** SDSSJ153830.55+085517.0. Same details as in Figure A.6.
A.15. SDSSJ161458.33+144836.9

This object shows a very faint Fe II emission, as is typical of A1 spectra. A UV spectrum from the MOJAVE/2CM atlas for this source is presented in Torrealba et al. (2012). It is also one of the strongest radio-loud sources analysed in this work. Data from the Parkes 2.7 GHz Survey are shown in Savage et al. (1990). PKS 1937-101 is seen as a compact radio source after analysis of VLBI data (Lee et al. 2016). Brinkmann & Siebert (1995) has reported PKS 1937-101 as one of the most distant objects detected with the ROSAT survey (Voges 1993).

A.16. PKS 1937-101

Fig. A.15. SDSSJ161458.33+144836.9. Same details as in Figure A.6.

Fig. A.16. PKS 1937-101. Colours and lines as Figure A.1.
The UV spectrum used in the fittings was obtained through the digitisation of the spectrum from Barthel et al. (1990). However, since this spectrum presents a small wavelength range that does not account either for the 1900 Å blend or for He II λ1640, we analyse only the Si IV λ1397 and C IV λ1549 emission lines. A detailed comparison between this source and Q 1410+096 is performed in Deconto-Machado et al. (2022).

This quasar is the strongest radio-loud source from the present sample (Savage et al. 1990). The position of this source is not within the area covered by the FIRST catalogue.

Fig. A.17. PKS 2000-330. Top panels: Same details as in Figure A.6. (c) UV spectrum. Bottom panels: Fits for (d) Si IV λ1397 and (e) C IV λ1549. The UV spectrum was digitised from Barthel et al. (1990).
This source presents a $W([\text{O} \text{iii}]) \approx 0.45 \text{ Å}$. The low equivalent width makes it difficult to discern what corresponds to $[\text{O} \text{iii}] \lambda 4959,5007$ and to $\text{Fe II}$.

The UV region of this source is very unwieldy because of very broad absorption lines shortwards of $\text{C IV} \lambda 1459$. For the 1900 Å blend, we present two different fittings, one including blueshifted components for $\text{Al III} \lambda 1860$ and $\text{Si III} \lambda 1892$ and another without these lines. The motivation here is that if we do not include blueshifted components then the BC of the lines present a displacement of $-1640 \text{ km s}^{-1}$, which can be seen as an indicative of some outflowing gas.

**Fig. A.18.** SDSSJ210524.49+000407.3. *Top panels:* Colours and lines as in Figure A.1. *(c)* SDSS UV spectrum. **Bottom panels:** Fits for *(d)* $\text{C IV} \lambda 1549$ and *(e)* the 1900 Å blend.
This is another case in which the Fe\textsuperscript{II} contribution is estimated through the red side of the spectrum. It is difficult to set the [O\textsc{iii}]\,λλ\,4959,5007 NC at rest-frame since the region close to these lines is dominated by the Fe\textsuperscript{II} multiplets. Differently from the other Pop. A3 of the sample (SDSSJ005700.18+143737.7 and SDSSJ210524.49+000407.3), for this quasar it was not possible to reach a good \(\chi^2\), without including blueshifted components for Al\textsc{iii}\,λ\,1860 and Si\textsc{iii}\,λ\,1892. SDSSJ210831.56-063022.5 is a source that presents one of the widest H\textbeta\,BC of the sample. It could be that in this case the H\textbeta\,BLUE component has been underestimated, since we do find strong blueward asymmetries in the three fitted UV profiles.

Fig. A.19. SDSSJ210831.56-063022.5. Same details as in Figure A.6.
Fig. A.20. SDSSJ212329.46-005052.9. Same details as in Figure A.6.
A.21. PKS 2126-15

This object has been observed in the two runs. Since both observations can be used and present good S/N, we create a new spectrum by combining the two of them through the IRAF task scombine. The Fe II multiplets were fitted based on the shape seen in the red side of Hβ due to the fact that the blue side of Hβ is affected by noise and is almost at the border of the spectrum. In order to account for the [O III] λλ 4959,5007 contributions, it was necessary to include two blueshifted components, as can be seen in Fig. A.21. Some UV spectra were found but they do not include the regions we are interested in. PKS 2126-15 is also one of the four radio-loud quasars from the sample.

![Fig. A.21. PKS 2126-15. Colours and lines are the same as in Figure A.1.](image)
A.22. SDSSJ235808.54+012507.2

The spectrum of this source is of low S/N when compared with the other sources of the sample, which makes it difficult to find the correct intensity of the continuum. As a consequence, caution should be taken when considering the location of the continuum and the Fe II contribution especially in the blue part of the spectrum.

Fig. A.22. SDSSJ235808.54+012507.2. Same details as in Figure A.6.