Hubble Space Telescope ultraviolet spectroscopy of blazars: emission-line properties and black hole masses

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ABSTRACT

The ultraviolet (UV) spectra of 16 blazars (⟨z⟩ ≃ 1) from the archives of the Hubble Space Telescope Faint Object Spectrograph have been analysed in order to study in a systematic way the properties of their broad UV emission lines. We find that the luminosities of the most prominent and intense lines, Lyα and C IV λ1549, are similar to those of normal radio-loud quasars at comparable redshifts. However, the equivalent widths of blazar lines are significantly smaller than those of radio-loud quasars. Therefore, while the intrinsic broad-line region luminosity of blazars appears to be indistinguishable from that of radio-loud quasars, their continuum must be comparatively higher, most probably due to relativistic beaming. We have combined the UV luminosities of the debeamed continuum with the emitting gas velocity to derive estimates of the masses of the central supermassive black holes. The size of the broad-line region was computed in two ways: (1) via an empirical relationship between UV continuum luminosity and broad-line region size, and (2) through the external photon density required by blazar models to reproduce the inverse Compton components observed at γ-rays. The second method yields significantly different results from the first method, suggesting that it provides only a very rough estimate or a lower limit on the size of the broad-line region. We find that the average mass of the central black holes in blazars is ∼2.8 × 10^8 M_⊙, with a large dispersion, comparable to those computed for other radio-loud active galactic nuclei.

Key words: galaxies: active – BL Lacertae objects: general – gamma-rays: observations – ultraviolet: galaxies.

1 INTRODUCTION

Highly polarized quasars (HPQs; also referred to as flat-spectrum radio quasars) and, occasionally, BL Lacertae objects, collectively known as blazars, exhibit broad emission lines superimposed on their optical and ultraviolet (UV) continua (Netzer et al. 1994; Scarpa, Falomo & Pian 1995; Vermeulen et al. 1995; Corbett et al. 1996; Scarpa & Falomo 1997; Koratkar et al. 1998; Pian et al. 2002; D’Elia, Padovani & Landt 2003). Emission lines play an important role in the energetics of blazars: some models of multiwavelength blazar emission (Dermer & Schlickeiser 1993; Sikora, Begelman & Rees 1994; Ghisellini & Madau 1996) predict that the broad-line region (BLR) photons are Compton up-scattered to X- and γ-ray energies by the relativistic particles composing the jet plasma, and form luminous high-energy spectral components, which often dominate the overall blazar output (Mattox et al. 1997; Bloom et al. 1997; Wehrle et al. 1998; Hartman et al. 2001; Ballo et al. 2002; Pian et al. 2002). The role of broad-line emission in shaping the spectrum of different classes of blazars, however, has not been fully assessed (Fossati et al. 1998; Ghisellini et al. 1998; Padovani et al. 2003).

More generally, the characteristics of the BLR of blazars may help in investigating the interplay between the accretion disc and the relativistic jet, which is more prominent in blazars than in normal quasi-stellar objects (QSOs, quasars) and Seyfert galaxies (Celotti, Padovani & Ghisellini 1997; Maraschi & Tavecchio 2003; D’Elia et al. 2003; Wang, Luo & Ho 2004). Active galactic nuclei (AGN) broad emission lines may be used also to estimate the masses of the compact objects residing in the nuclear centres, most likely supermassive black holes (BHs), by exploiting their dynamical effect on the line-emitting gas clouds. The application of the virial theorem requires that the size of the BLR is determined either with direct methods (reverberation mapping technique, Peterson & Wandel 2000; Kaspi et al. 2000; Peterson et al. 2004), or with indirect arguments (Kaspi et al. 2000; Vestergaard 2002). In the latter case the uncertainties are obviously larger, and the methods must

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Table 1. Parameters of blazars observed with HST FOS.

<table>
<thead>
<tr>
<th>Object</th>
<th>Alt. name</th>
<th>z</th>
<th>$E(B-V)$</th>
<th>Date</th>
<th>Range$^b$</th>
<th>$\alpha_{c}$ $^c$</th>
<th>$f_{1350}^d$</th>
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$^a$From the maps of Schlegel et al. (1998). $^b$Observed wavelength range, in Å. $^c$Spectral index of the power law fitted to the dereddened spectra ($\alpha_{c} \propto \lambda^{-\alpha_{c}}$). $^d$Normalization of the dereddened power-law continuum at 1350 Å (rest frame), in $10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$.

be tested carefully. Since this has important consequences on the evolution and demographics of AGNs, it is crucial to accomplish these measurements both for low- and high-redshift sources. This approach has been adopted in the estimation of BH masses of large samples of quasars based on optical emission lines (Woo & Urry 2002; McLure & Dunlop 2004). The advantage of using UV rather than optical emission lines is that the former correspond to a higher ionization state and are therefore presumably more representative of the dynamics close to the central massive object.

In this paper we present the analysis of the broad and intense UV emission lines of 16 blazars observed by the Hubble Space Telescope (HST) and the Faint Object Spectrograph (FOS). Previous studies of AGN UV spectra have been carried out by Bechtold et al. (2002), who focused on the absorption systems, by Kuraszkiewicz et al. (2002), who recalibrated the pre-COSTAR AGN spectra. We concentrate here on the UV spectra of blazars. Based on the radiative and kinematic properties of the broad emission-line region (BLR), we measure the luminosities of their BLRs and derive estimates of the BLR sizes and of the central BH masses.

We adopt the ‘concordant cosmology’, $\Omega_0 = 0.3$, $\Omega_{\Lambda} = 0.7$, and assume $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$ (Spergel et al. 2003). Luminosities reported by other authors and used in this paper have been transformed into this cosmology.

## 2 Sample Selection and Data Analysis

We have retrieved from the HST archive1 all pre- and post-COSTAR FOS grating spectra of sources previously classified as blazars (Wall & Peacock 1985; Impy & Tapia 1988, 1990; Impy, Lawrence & Tapia 1991; Stickel et al. 1991; Stocke et al. 1991; Padovani & Urry 1992; Wills et al. 1992; Perlman et al. 1996). We also included in our final list PKS 1229−021, which, despite having low polarization (Wills et al. 1992), is considered a blazar because of significant emission at MeV–GeV frequencies (Hartman et al. 1999), and 3C 273, which has intermediate properties between those of blazars (strong radio emission, superluminal motion, $\gamma$-ray emission, jet emission dominance at hard X-ray energies, e.g. Haardt et al. 1998; Grandi & Palumbo 2004) and those of Seyfert galaxies (broad emission lines, big blue bump). We selected spectra taken with high-resolution gratings in the UV region (G130H, G190H, G270H, G400H).

This search yielded 24 objects with measurable spectra. Spectra taken with the same grating within 1 d were averaged to increase the signal-to-noise ratio. For this work we have considered only the 16 sources with significant (larger than 3$\sigma$) emission-line detections. These are reported in Table 1.

For six sources there are also low-resolution grating (G160L) observations in the archive, obtained nearly simultaneously with the high-resolution spectra (i.e. within 1 d). Since the line parameters and spectral indices derived from the former are not significantly different from those measured in the high-resolution spectra, we have neglected these spectra.

Although the considered objects do not represent a complete sample, they form a sizeable data set to investigate the UV line properties of blazars.

After applying a correction for the Galactic absorption using the maps of Schlegel, Finkbeiner & Davis (1998) and the extinction curve of Cardelli, Clayton & Mathis (1989), we measured the equivalent widths (EWs), the intensities and the full width at half-maximum (FWHM) values of the emission lines, fitting a linear local continuum on each side of the line (see Table 2). The EW

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1 Using MAST, the Multi-mission Archive at STScI; see http://archive.stsci.edu
uncertainties were estimated by assuming $2\sigma$ variations of the local continuum.

For each object we have combined the spectra taken quasi-simultaneously (within 1 d) with different gratings, excluded the regions affected by emission or absorption features, binned the signal in 20–50 Å wavelength intervals, and fitted the continuum with a power law. To account for calibration uncertainties of the data, we added a 5 per cent systematic error to the statistical errors. The derived power-law spectral indices and flux normalizations are given in Table 1.

A similar analysis of the continuum and line properties of these objects has been presented in Kuraszkiewicz et al. (2002, 2004).

3 RESULTS

The redshifts of our objects (see Table 1) range between $z = 0.158$ and 1.404, with an average value of $\langle z \rangle = 0.84 \pm 0.31$. Thus, the lines typically detected in our FOS spectra are Ly$\beta$, Ly$\alpha$, C IV $\lambda 1549$, C III] $\lambda 1909$, Si IV $\lambda 1400$ and in some cases Mg II $\lambda 2798$. We report in Table 1 the spectral indices and normalizations of the UV continua and in Table 2 the EW and the FWHM values of the emission lines.

In three cases (3C 273, 345 and 454.3) observations at more than one epoch are available. Variations of line and continuum emission are observed, with maximum amplitudes of factors of $\sim 2$ and $7$, respectively. However, the observations are too limited and sparse to allow a meaningful assessment of correlated line and continuum variability.

In Section 3.1 we describe the average properties of the emission lines of blazars in the UV spectral region; in Section 3.2 we use the line and continuum properties of the UV spectra to estimate the masses of the central BHs.

3.1 Emission-line properties

In order to produce a representative high signal-to-noise ratio UV spectrum of blazars, we have combined all the UV spectra in our data set. Each spectrum was first reduced to rest frame and then normalized to its average continuum flux. The resulting composite blazar spectrum, normalized to unity at the reference wavelength of 1500 Å, is shown in Fig. 1. The EWs, relative intensities and FWHMs of the emission lines of the composite spectrum are given in Table 3.

The composite spectrum of blazars is similar to that of normal QSOs. The line ratios of blazars and normal AGNs are also not significantly different. This is illustrated in Fig. 2, where we report the luminosities of the Ly$\alpha$ and C IV $\lambda 1549$ lines of blazars, compared with those of a list of radio-loud quasars (RLQs) observed by HST FOS (Wills et al. 1995). Note that in this list of RLQs there are eight objects in common with our sample of blazars; therefore, for the purpose of the comparison, these eight sources have been considered as blazars and have been excluded from the RLQ list. We also compare with the RLQ 3C 390 (1845+79, $z = 0.056$), which has hybrid properties, i.e. it has substantial polarization (1.3 per cent, Impey et al. 1991), but is lobe-dominated at radio wavelengths (Ghisellini et al. 1993). Fig. 2 shows that the intensity ratio of Ly$\alpha$ versus the C IV $\lambda 1549$ in blazars is consistent with that exhibited by normal RLQs.

More generally, we have compared in Table 3 the average intensity ratios of the lines we detect in our composite blazar spectrum with those reported by other authors for larger samples of QSOs or RLQs (Francis et al. 1991; Zheng et al. 1997; Telfer et al. 2002). Except for the C III] $\lambda 1909$ line, which appears somewhat underluminous in blazars, there is good overall agreement. This comparison suggests that the structure and physical state of the BLR in blazars and normal RLQs are indistinguishable. This is also confirmed by the comparison of the Ly$\alpha$ line luminosities. In Fig. 3 we report the continuum luminosity at 1350 Å as a function of the Ly$\alpha$ luminosity for blazars and RLQs. With the exception of 3C 390, which is at relatively low redshift, the blazars and RLQs have a similar range of Ly$\alpha$ luminosities. The averages of the logarithmic distributions, in erg s$^{-1}$, are $(\log L(Ly\alpha)) = 44.55 \pm 0.11$ and $(\log L(Ly\alpha)) = 44.72 \pm 0.12$ for blazars and RLQs, respectively (the uncertainties represent the errors associated with the averages, i.e. the standard deviations divided by the square root of the number of objects). However, because of relativistic beaming, blazars have more luminous continua than RLQs, i.e. blazer lines have smaller EWs (see Fig. 3). While RLQ emission lines, for any continuum luminosity, have EWs between 100 and 1000 Å, part of the blazars exhibit line EWs between 10 and 100 Å, and these have the most strongly boosted continua. From comparison with the RLQs, we have estimated the luminosity enhancement due to beaming.

Relativistic aberration affects the non-thermal synchrotron luminosity and depends on the fourth power (for a jet geometry) of the relativistic Doppler factor $\delta$ (equal to $[1 - v \cos \theta]^3$). RLQs are thought to be the parent population of blazars: their jets are directed away from the line of sight, so that their luminosities are only weakly affected by relativistic beaming. Therefore, we have estimated the beaming amplification for the blazars by assuming that their continuum luminosities should exhibit a dependence on Ly$\alpha$ line luminosities similar to that of RLQs (Fig. 3). We fitted the RLQ line (in erg s$^{-1}$) and continuum (in erg s$^{-1}$ Å$^{-1}$) luminosities to a power law and obtained the dependence

$$L(1350 \, \text{Å}) = 0.46 \times 10^{-3} L(Ly\alpha)^{1.02},$$

which has a scatter of 0.2 dex in $L(1350 \, \text{Å})$. We will use this relationship in Section 3.2.1 to correct the continuum luminosities of blazars for the beaming.

3.2 Black hole masses

Under the assumption that the dominant mechanism responsible for the width of the broad emission lines is the gravitational potential of the central supermassive BH, and that the linewidths reflect the Keplerian velocities of the line-emitting material in a virialized system (Wandel, Peterson & Malkan 1999; McLure & Dunlop 2001), the BH mass $M_{BH}$ is given by

$$M_{BH} = G^{-1} v^2 R_{BLR},$$

where $v$ is the velocity of the gas gravitationally bound to the central BH, $R_{BLR}$ is the size of the BLR, and $G$ is the gravitational constant. The velocity $v$ can be obtained directly from the FWHM of the broad emission lines ($v = f \times \text{FWHM}$), where $f$ is a factor that depends on the geometry and kinematics of the BLR (e.g. McLure & Dunlop 2002; Vestergaard 2002).

3.2.1 Size of the BLR

The most reliable method to derive $R_{BLR}$ is through the reverberation mapping technique (e.g. Peterson et al. 2004, and references therein). This uses the time lag of the emission-line light curve with respect to the continuum light curve to determine the light crossing size of the BLR in AGNs. However, this method requires intensive monitoring of the UV continuum and of the lines, and can be used only for a limited number of objects (e.g. Korista et al. 1995; Onken & Peterson 2002), including one of our sources, 3C 273.
Table 2. Emission-line measurements.

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<th>Mg ii</th>
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<td>8.3 ± 0.7</td>
<td>50 ± 1</td>
<td>14</td>
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<td>16.8 ± 0.4</td>
<td>14 ± 3</td>
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</tbody>
</table>

<sup>a</sup>The Lyα and Lyβ line EW measurements may have a residual contamination by the N v λ1240 and O vi λ1034 lines, respectively. This possible contamination does not exceed ∼10 per cent. We have deblended the contamination in the FWHM measurements.

<sup>b</sup>At rest frame, in Å. Uncertainties on the FWHM values are about 15 per cent.

<sup>c</sup>This line has an asymmetric profile, with a more prominent red wing.

<sup>d</sup>1991 January 16.8.
<sup>e</sup>1991 July 9.4.
<sup>f</sup>1992 June 7.9.
<sup>g</sup>1995 August 20.4.
<sup>h</sup>1991 September 11.9.
<sup>i</sup>1991 November 15.3.
<sup>j</sup>1995 August 19.4.
Türlер (2005). An alternative way to estimate $R_{\text{BLR}}$ is to use the empirical relationship found between $R_{\text{BLR}}$ and the optical continuum luminosity (Kaspi et al. 2000).

We have derived this relationship in the UV for a sample of 15 PG quasars and 10 type 1 Seyfert galaxies having BLR radii determined via reverberation mapping in the optical (Kaspi et al. 2000) and measured UV spectra (Vestergaard 2002). One of the PG quasars is 3C 273, which is also a member of our blazar sample. For this object, we corrected the continuum luminosity for the beaming effect (see equation 1). For one of the Seyferts, NGC 4151, the UV continuum of which varies with high amplitude, we remeasured the continuum luminosity at 1350 Å from the average International Ultraviolet Explorer (IUE) spectrum. These quantities are reported in Fig. 4. We fitted the BLR radii and the luminosities at 1350 Å (rest frame) with a power law and obtained the following relationship:

$$R_{\text{BLR}} = (22.4 \pm 0.8) \left( \frac{\lambda L_{\lambda}(1350 \text{ Å})}{10^{44} \text{ erg s}^{-1}} \right)^{0.61 \pm 0.02} \text{ light-day}. \quad (3)$$

If we exclude 3C 273 from the fit, the result is unchanged (the power-law index is 0.60 ± 0.02 in this case). We note that the slope in equation (3) is consistent with that determined in the same wavelength range by Kaspi et al. (2005, index 0.56 ± 0.05); is slightly flatter than that found in the optical by Kaspi et al. (2000, index 0.70 ± 0.03) and slightly steeper than that found by McLure & Jarvis (2002, index 0.50 ± 0.02) at 3000 Å, based on a very similar sample of PG quasars and Seyfert galaxies.

Since the relationship between the BLR radius and continuum luminosity is supposed to be valid in the case of a thermal continuum (see also discussion in Paltani & Türlер 2005), we must correct the blazar UV continuum luminosities for the effect of relativistic beaming.

For the blazars with continuum luminosity exceeding the power-law dependence between the RLQ line and continuum luminosities (equation 1), we adopted the continuum luminosities computed with equation (1) at the corresponding line luminosity, and derived the BLR radii through equation (3). These are reported in Table 4. The correction of the continuum luminosity is relevant (i.e. larger than ∼3 times the scatter) for four objects (see Fig. 3). We note that our estimate of the BLR radius of 3C 273 is consistent with that reported by Paltani & Türlер (2005).

An alternative, independent method for evaluating $R_{\text{BLR}}$ consists in coupling the luminosity of the BLR with the information carried by the multwavelength spectrum of the blazar. Since blazars, among all AGNs, are the only ones with a spectrum extending to γ-rays, this method is specific for the blazar class of AGNs.

Ten of our blazars have multiwavelength energy distributions that have been fitted with synchrotron and inverse Compton radiation

![Figure 1. Composite UV spectrum of blazars obtained from the average of 16 spectra. The most prominent emission lines are labelled.](image)

![Figure 2. Luminosities of C IV λ1549 and Lyα emission lines for the blazars in our list (filled circles). Line measurements of a given source at multiple epochs have not been averaged. The Lyα and C IV λ1549 emission-line intensities have been normalized to their respective average values. The solid line is the expected C IV λ1549 to Lyα intensity ratio, $L(\text{C IV} \lambda 1549) = 0.63 \times L(\text{Lyα})$ (e.g. Francis et al. 1991). The dashed line is the least-squares regression line, $L(\text{C IV} \lambda 1549) = 8.3 \times L(\text{Lyα})^{0.73}$. For comparison, the line luminosities of 19 RLQs (open circles) from Wills et al. (1995) and of 3C 390 (filled triangle) are also shown.](image)

**Table 3.** Composite ultraviolet blazar spectrum.

<table>
<thead>
<tr>
<th>Line</th>
<th>EW*</th>
<th>FWHM*</th>
<th>Rel. intensity*</th>
<th>Ratio*</th>
<th>Ratio (LBQS) t</th>
<th>Ratio (RLQa) f</th>
<th>Ratio (RLQb) f</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lyβ</td>
<td>6.5 ± 0.5</td>
<td>10</td>
<td>8.9 ± 0.5</td>
<td>10.6</td>
<td>9.3</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>Lyα</td>
<td>71 ± 3</td>
<td>22</td>
<td>84 ± 3</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Si IV</td>
<td>5.2 ± 0.7</td>
<td>21</td>
<td>5.6 ± 0.7</td>
<td>6.6</td>
<td>19</td>
<td>6.8</td>
<td>8.6</td>
</tr>
<tr>
<td>C IV</td>
<td>45 ± 2</td>
<td>20</td>
<td>45 ± 1</td>
<td>53</td>
<td>63</td>
<td>66</td>
<td>52</td>
</tr>
<tr>
<td>C III</td>
<td>7 ± 1</td>
<td>23</td>
<td>6.6 ± 0.7</td>
<td>7.8</td>
<td>29</td>
<td>11</td>
<td>13.2</td>
</tr>
<tr>
<td>Mg II</td>
<td>19 ± 2</td>
<td>30</td>
<td>16 ± 1</td>
<td>19</td>
<td>34</td>
<td>24</td>
<td>22.3</td>
</tr>
</tbody>
</table>

*At rest frame, in Å. Uncertainties are about ∼15 per cent. Obtained from EW and continuum normalized to the flux at 1500 Å (rest frame). Average percentage intensity ratio with respect to Lyα as resulting from our measurements. Same as in column 5 for 718 objects in the Large Bright Quasar Survey (Francis et al. 1991). Same as in column 5 for 60 radio-loud quasars (Zheng et al. 1997). Same as in column 5 for 107 radio-loud quasars (Telfer et al. 2002).
components (Ghisellini et al. 1998). The latter component dominates at the X- and γ-ray energies and originates from the scattering of relativistic electrons off both synchrotron photons (internal to the jet) and external radiation fields. These include broad-line photons, the density of which, \( U_{\text{ext}} \), is thus estimated through the multiwavelength spectral fit.

Following the procedure adopted by Celotti et al. (1997), we reconstructed the total luminosity of the BLR for each of our sources by using the intensities of the observed UV emission lines and by assuming for the unobserved lines the line ratios of an average quasar spectrum (Francis et al. 1991). These derived BLR luminosities are reported in Table 4.

From the fitted densities of the external photons \( U_{\text{ext}} \) and from the observed BLR luminosities, the size of the BLR, \( R_{\text{BLR}} \), can be derived according to

\[
R_{\text{BLR}} = \frac{L_{\text{BLR}}}{4\pi c U_{\text{ext}} \delta^2},
\]

where \( \delta \) is the relativistic Doppler factor required by the multiwave-length modelling. The BLR radii computed with equation (4) are reported in Table 4. We have identified this second method as the ‘spectral energy distribution (SED) method’, in order to distinguish it from the one based on the empirical determination of \( R_{\text{BLR}} \) from the continuum luminosity. No clear correlation is found between the BLR radii determined with the two methods. One probable explanation of the discrepancy is that the radiation density of the BLR is generally smaller than the parameter \( U_{\text{ext}} \) obtained with multiwavelength fits. This parameter includes not only the BLR photons, but also additional contributions, such as photons coming directly from the accretion disc, or produced by the dusty torus, or by larger regions of the jet (Ghisellini, private communication). Thus, the SED method may underestimate the BLR sizes (and therefore the BH masses) in some cases. Moreover, the uncertainties associated with the SED fitting parameters are large. Therefore, although we had proposed the ‘SED’ method for BH mass determination in an individual source (PKS 0537−441, Pian et al. 2002), it appears that this method cannot be generalized.

### 3.2.2 Mass estimates

In order to evaluate the BH masses of our objects, we have used equations (2) and (3), adopting a standard value of \( f = \sqrt{3}/2 \) for the kinematic factor, corresponding to an isotropic distribution of the BLR clouds (Wandel 1999; Kaspi et al. 2000; Vestergaard 2002), which yields virial BH masses consistent with those derived from the \( M_{\text{BH}} \) versus \( L_{\text{bulge}} \) relationship (Labita, Falomo & Treves, in preparation). After setting \( v_{\text{FWHM}} \) to suitable units we obtain the relation

\[
M_{\text{BH}} = 3.26 \times 10^6 \left[ \frac{L_{\text{BLR}}(1350 \text{ Å})}{10^{44} \text{ erg s}^{-1}} \right]^{0.61} \left( \frac{v_{\text{FWHM}}}{10^3 \text{ km s}^{-1}} \right)^2 M_\odot.
\]

Vestergaard (2002) also derives a formula for the central BH mass, based on the continuum measurements at the rest-frame wavelength of 1350 Å of a sample of 26 AGN with BLR radii determined by reverberation mapping. However, this relationship was calibrated against the BH masses determined from optical measurements, and not directly from the BLR size, as we do.

By using equation (5) with the beaming-corrected \( L(1350 \text{ Å}) \) luminosities and \( v_{\text{FWHM}} \) estimated from our spectra, we have computed the central BH masses. For consistency with Vestergaard (2002) we have used the FWHM of C IV λ1549. These masses are reported in column 5 of Table 4, and in Fig. 5, where they are compared with those computed with our equation (5) for a sample of PG quasars, for which Vestergaard (2002) reports UV luminosities and C IV λ1549 line FWHM values. The blazar BH masses are statistically consistent with those of quasars: the averages of the logarithmic distributions, in solar masses, are \( \log M_{\text{BH}} = 8.31 \pm 0.10 \) and \( \log M_{\text{BH}} = 8.42 \pm 0.08 \) for blazars and RLQs, respectively (the uncertainties represent the errors associated with the averages, i.e. the standard deviations divided by the square root of the number of objects).
Table 4. BLR luminosities and central black hole masses.

<table>
<thead>
<tr>
<th>Object</th>
<th>$L_{\text{BLR}}^a$</th>
<th>$R_{\text{BLR}}^b$</th>
<th>$R_{\text{BLR,SED}}^c$</th>
<th>$M_{\text{BH}}^d$</th>
<th>$M_{\text{BH,LL}}^e$</th>
<th>$M_{\text{BH,WU}}^f$</th>
<th>$M_{\text{BH,W}}^g$</th>
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$^a$Luminosity of the BLR, in units of $10^{44}$ erg s$^{-1}$. $^b$Size of the BLR computed via equation (3), in light-day. $^c$Size of the BLR computed using the SED method (equation 4), in light-day. $^d$Mass of the central BH computed using equation (5), in units of $10^8 M_\odot$. The statistical uncertainties, dominated by the scatter of equation (3), are about a factor of 2. $^e$Mass of the central BH from Liang & Liu (2003). $^f$Mass of the central BH from Woo & Urry (2002). $^g$Mass of the central BH from Wang et al. (2004).

Figure 5. Histograms of central BH masses of AGNs. The lightly hatched area represents the masses of PG quasars computed with equation (5) from the luminosities and C IV $\lambda 1549$ emission-line FWHM values reported by Vestergaard (2002). The heavily hatched area represents the BH masses of our blazar sample. Mass estimates obtained for the same source at different epochs have been averaged.

For comparison, we have also computed the blazar BH masses using Vestergaard’s relationship (equation 8 of Vestergaard 2002), with our measured blazar luminosities and FWHM values of the C IV $\lambda 1549$ line. These are systematically lower than the corresponding ones determined using equation (5), by a factor of 1.4–2. We have also compared our estimated BH masses with those determined for the same blazars by other authors: a number of our objects are in common with the samples of Liang & Liu (2003), Woo & Urry (2002) and Wang et al. (2004). Their mass estimates have been reported in the last three columns of Table 4: our masses are generally smaller. This may be partially due to our correction of the continuum luminosity for the beaming effect. In particular, this must be the case for two of the four objects in our sample with the most strongly beamed continuum, 3C 279 and PKS 0537−441.

We do not find a correlation of the BH mass with redshift for our blazar sample.

4 SUMMARY AND CONCLUSIONS

We have studied the properties of the UV emission lines of blazars, mostly from single-epoch HST FOS spectra, and found that the average blazar UV spectrum is similar to that of RLQs. This is the sum of a thermal and non-thermal component. Our targets are mainly HPQs and low-frequency peaked BL Lacs (Padovani & Giommi 1995; Fossati et al. 1998), where the emission of the non-thermal synchrotron component peaks at optical/infrared frequencies. Therefore, a large relative contribution from the thermal accretion disc is expected in the UV region (e.g. Bregman et al. 1986). This is clearly evident from the spectral energy distribution of 3C 273 (Ulrich et al. 1980; Courvoisier 1998) and may be significant in 3C 279 (Pian et al. 1999).

With the aim of estimating central BH masses of blazars, we have assumed Keplerian conditions in the BLR gas motion and have evaluated the BLR size using the results of a fit of UV luminosities and BLR radii of a sample of QSOs having BLR sizes determined via reverberation mapping in the optical. We have derived a relationship between $R_{\text{BLR}}$ and luminosity in the UV domain (1350 Å at rest frame), which exhibits a slope consistent with that of Kaspi et al. (2005), although it is slightly flatter and steeper than proposed in the optical and near-UV by Kaspi et al. (2000) and McLure & Jarvis (2002), respectively.

For those 10 blazars having multiwavelength spectral fits we have also applied an independent method of BLR size determination, based on the combination of the observed $L_{\text{BLR}}$ and fitted external
radiation density (‘SED’ method). We have not found a clear correlation between the BLR sizes obtained with the two methods, with the largest deviations observed in the sense of a deficit of the ‘SED’ radii with respect to those obtained with the empirical $R_{BLR}$ versus $\lambda L_{\lambda}$ relationship. We conclude that the SED method yields a BLR size inconsistent with that derived from the continuum luminosity.

Our estimated BH masses have an average of $(2.8 \pm 2.0) \times 10^8 M_\odot$ (the quoted uncertainty is the standard deviation) and are comparable with those of lower-redshift blazars, estimated with different methods (Barth, Ho & Sargent 2003; Falomo et al. 2003).

The distribution of our blazar BH masses computed with equation (5) is consistent with the distribution of the PG quasar masses computed with the same equation. These results suggest that the differences between radio-powerful sources and radio-weak ones are not due to the mass of the BHs residing at their centres. However, the validity of this conclusion at intermediate/high redshifts must be corroborated by the analysis of wider samples of homogeneous data sets. Moreover, further intensive spectroscopic monitoring of the brightest blazars at optical and UV wavelengths is required, in order to construct well-sampled continuum and emission-line light curves for the application of the reverberation mapping technique.

ACKNOWLEDGMENTS

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