C iv AND C iii] REVERBERATION MAPPING OF THE LUMINOUS QUASAR PG 1247+267

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ABSTRACT

So far the masses of about 50 active galactic nuclei (AGNs) have been measured through the reverberation mapping technique (RM). Most measurements have been performed for objects of moderate luminosity and redshift, based on Hβ, which is also used to calibrate the scaling relation that allows single-epoch (SE) mass determination based on AGN luminosity and the width of different emission lines. Due to the complex structure and gas dynamics of the relevant emission region, the SE masses obtained from the C iv(1549 Å) line show a large spread around the mean values. Direct RM measures of C iv exist for only six AGNs of low luminosity and redshift, and only one luminous quasar. Since 2003, we have collected photometric and spectroscopic observations of PG1247+267, the most luminous quasar ever analyzed for RM. We provide light curves for the continuum and for C iv(1549 Å) and C iii](1909 Å), and measures of the reverberation time lags based on the SPEAR method. The sizes of the line emission regions assume a ratio of $R_{\text{C iii}]/R_{\text{C iv}} \sim 2$, similar to the case of Seyfert galaxies, indicating for the first time a similar ionization stratification in a luminous quasar and low-luminosity nuclei. Due to the relatively small size of the broad line region and the relatively narrow line widths, we estimate a small mass and an anomalously high Eddington ratio. We discuss the possibility that either the shape of the emission region or an amplification of the luminosity caused by gravitational lensing may be partly responsible for the result.

Key words: galaxies: active – quasars: emission lines – quasars: general – quasars: individual (PG 1247+267) – quasars: supermassive black holes

1. INTRODUCTION

Reverberation mapping (RM) has played a crucial role in the study of the structure of active galactic nuclei (AGNs). Spectroscopic monitoring in the UV/optical band allows us to measure emission line flux changes that represent the “echo” of far-UV ionizing continuum variations, which in turn are closely related to the observed near-UV continuum variations. The delay $\tau_l$ of the echo, i.e., of line variation with respect to continuum changes, is measured through continuum-line cross-correlation and provides the luminosity-weighted average distance, $R = c \cdot \tau_l$, of the line-emitting region from the (point-like) continuum source, where $c$ is the speed of light (Blandford & McKee 1982; Peterson 1993). Until 1999, 17 AGNs with $\lambda L_\beta(5100 \, \text{Å}) \lesssim 1.5 \times 10^{44} \, \text{erg s}^{-1}$ had been studied (see Wandel et al. 1999, and references therein), resulting in measurements of the sizes of their broad line regions (BLR) and demonstrating a stratification of ionization, with the higher ionization lines responding more rapidly to continuum changes. Combining the size, $R$, with a measure of the typical velocity, $\Delta V$, of the emitting BLR clouds, assumed to be in Keplerian orbits, it is possible to derive a virial estimate of the black hole mass $M_\text{BH} = f c \tau_l \Delta V^2 / G$ of the central black hole, where $G$ is the gravitational constant and $f$ is a scaling factor depending on the geometry of the BLR and the specific definition adopted for $\Delta V$ (see Section 4). The extension of these results with the addition of a sample of 17 quasars (QSO) with luminosities of $\lambda L_\beta(5100 \, \text{Å})$ up to $\sim 6.5 \times 10^{45} \, \text{erg s}^{-1}$ allowed Kaspi et al. (2000) to establish a $R \propto L^\beta$-type size–luminosity scaling relation in a luminosity range covering more than four decades (Kaspi et al. 2005; Bentz et al. 2006, 2009). This relation can be used to estimate the BH mass based on $\Delta V$ and $L$ measured from single epoch (SE) spectra (Vestergaard 2002; McLure & Jarvis 2002), raising the possibility of estimating the BH mass of thousands of QSOs/AGNs, analyzing their luminosity function at different redshifts, and following the BH-galaxy co-evolution in cosmic time (Shen & Kelly 2012). The widths of different lines, Hβ, C iv, Mg ii, are used depending on the redshift and wavelength range of optical/IR ground-based observations. However, the scaling relations for C iv and Mg ii (McLure & Jarvis 2002; Vestergaard & Peterson 2006; McGill et al. 2008) are not obtained from the few direct RM measures of these lines, but are instead calibrated on the mass scale based on Hβ time lags, which represent the majority of RM measures to date. The latter are currently limited to objects with $\lambda L_\beta(5100 \, \text{Å}) \lesssim 10^{46} \, \text{erg s}^{-1}$ and $z < 0.3$ (Bentz et al. 2013, and references therein). According to Netzer (2003), the largest black hole masses deduced from these extrapolations, occurring in objects with the highest luminosities, would exceed $10^{10} M_\odot$ and, if converted to host galaxy mass and luminosity through the statistical relation between the black hole mass, galaxy bulge mass, and stellar velocity dispersion, would imply galactic bulge masses of $M_{\text{bulge}} \gtrsim 10^{11} M_\odot$ and stellar velocity dispersions exceeding 700 km s$^{-1}$ which have never been observed, suggesting that either the $M_{\text{BH}}-M_{\text{bulge}}$ correlations observed in the local universe are different at higher redshift, or that the observed size–luminosity relationship in low-luminosity AGNs does not extend to very high luminosities. Vestergaard (2004) pointed out that the space density of such luminous quasars is so low that their local absence does not mean that they do not exist. In any case, exploring the validity or failure of the size–luminosity scaling relation is of crucial importance, not only to understand the physical conditions in the most luminous QSOs, but also because most of the AGN mass estimates are based on this
unconfirmed extrapolation, which could lead to uncertain or biased conclusions concerning the evolution of the AGN mass function in cosmic time. To measure the BRL size and BH mass of luminous QSOs, in 2003 we started a monitoring campaign of four high-luminosity \((L > 5 \times 10^{46} \text{ erg s}^{-1})\) and intermediate-redshift \((2 < z < 4)\) objects with the Copernico 1.82 m telescope in Asiago (Italy) and the Cassini 1.52 m telescope in Loiano (Italy). Trevese et al. (2007) published some results for the QSOs PG 1634+706, with \(z = 1.337\), and PG 1247+267, with \(z = 2.048\), demonstrating the detectability of the emission line variations. A study of the broad absorption line variability of the luminous quasar APM 08279+5255 (Trevese et al. 2013; Saturni et al. 2014) and preliminary results on RM for PG 1247+267 (Perna et al. 2014) were also presented.

At \(z > 2\), \(H_\beta\) is no longer observable in the optical band and reverberation can be observed for the \(\text{C}\text{ iv}\) \((\lambda 1909 \text{ Å})\) and \(\text{C}\text{ iv}(\lambda 1549 \text{ Å})\) lines. Reverberation measurements of the \(\text{C}\text{ iv}\) line are available only for a handful of low-luminosity \((\lambda L_\lambda(1350 \text{ Å}) \lesssim 10^{43} \text{ erg s}^{-1})\) and low-redshift \((z < 0.06)\) AGNs observed in the ultraviolet from space. In addition, Kaspi et al. (2007) presented the first results of an RM campaign begun in 1999 with the HET 11 m telescope (Ramsey et al. 1998) providing a first tentative mass estimate for SS 0836+071, a luminous \((\lambda L_\lambda(1350 \text{ Å}) \approx 1.12 \pm 0.16 \times 10^{47} \text{ erg s}^{-1})\) QSO at \(z = 2.172\), based on \(\text{C}\text{ iv}\) RM. More recently, several studies discussed the unreliability of \(\text{C}\text{ iv}\)-based mass estimates, due to gas outflows strongly affecting the profile of this line (Netzer et al. 2007; Sulentic et al. 2007; Marziani & Sulentic 2012; Denney 2012). The fact that there is no consensus about the scatter and possible biases between \(\text{C}\text{ iv}\)-based and \(H\beta\)-based BH masses (Greene et al. 2010; Assef et al. 2011; Runnoe et al. 2013) further increases the importance of RM measure of the size of the emitting region in order to constrain wind models and eventually lead to a consistent picture that includes the BH mass, gas outflow, and possibly its feedback on the host galaxy.

In this work, we present the \(\text{C}\text{ iv}, \text{C}\text{ iii}\), and continuum light curves obtained for PG 1247+267, and we estimate the relevant time lags based on a method proposed by Zu et al. (2011). We also analyze the shape of the \(\text{C}\text{ iv}\) and \(\text{C}\text{ iii}\) lines and discuss the determination of the virial mass of the central BH, the corresponding value of the Eddington ratio, and possible explanations of the anomalously high values found. The paper is organized as follows. In Section 2, we describe the observation and data reduction. In Section 3, we discuss the estimate of the time lags. In Section 4, we discuss the mass estimates based on \(\text{C}\text{ iv}, \text{C}\text{ iii}\) RM. In Section 5, we draw our conclusions.

Throughout this paper, we adopt the cosmology \(H_0 = 70 \text{ km s}^{-1}\), Mpc\(^{-1}\), \(\Omega_m = 0.3\), and \(\Omega_\Lambda = 0.7\).

2.  OBSERVATIONS AND DATA REDUCTION

The majority of observations were carried out using the Faint Object Spectrograph and Camera AFOSC at the Copernico 1.82 m telescope in Asiago (Italy). We measured relative spectrophotometric variations by including a reference star in a wide \((8.44)\) slit to avoid differential flux losses caused by atmospheric refraction. The reference star is the object at \(\alpha = 125011.44, \delta = +263332.1\) (J2000), with \(V = 13.824\) (Pickles & Depagne 2010). At each epoch, the observations consist of two consecutive exposures of \(\approx 1800\) s. The typical resolution is \(\approx 15\) Å in the spectral range 3500–8500 Å. Details are described in Trevese et al. (2007). The QSO and reference star uncalibrated spectra, \(Q(\lambda)\) and \(S(\lambda)\), respectively, are extracted by the standard IRAF\(^6\) procedures, and the ratio \(\mu(\lambda) = Q(\lambda)/S(\lambda)\) is computed for each exposure \(k = 1, 2\). This quantity is independent of extinction variations and allows us to reject inconsistent exposure pairs whenever \(|\mu(2)/\mu(1) - 1|\) averaged over 500 Å exceeds 0.04. This procedure also allows us to compute the relative flux differences between the two exposures, which are used to estimate the statistical errors on continuum and emission line fluxes. At the \(i\)th epoch \(t_i\), pairs of spectra for both the QSO and the reference star were co-added to compute the ratio \(\mu_i(\lambda) = Q_i(\lambda)/S_i(\lambda) = (Q(1) + Q(2))/(S(1) + S(2))\). Data separated by less than one day are combined into a single epoch data point.

The flux-calibrated spectrum of the star \(F_S(\lambda)\) was obtained at a single reference epoch and the calibrated quasar spectra were obtained for each epoch as \(F_S^0(\lambda) = \mu_i(\lambda)F_S(\lambda)\). We stress that the spectra are independent of extinction changes and detector response, and thus spectral variations are also independent of telescope, detector, and calibration. This allows us to include four spectra taken at the 1.5 m Cassini telescope of the Loiano Observatory with the BFOSC camera. At each epoch, two exposures of 2700 s were taken with about the same resolution of AFOSC spectra.

Although the following reverberation analysis is independent of the absolute calibration, we have now revised the calibration of the spectra for possible future uses. This has been done by multiplying the calibrated spectrum of the reference star by a constant factor which makes its \(V\) magnitude, as computed from the spectrum adopting the Bessell (1990) filter profile, equal to \(V = 13.824\) as given by Pickles & Depagne (2010).

Figure 1 shows the flux-calibrated average spectrum and the rms spectrum of PG 1247+267. A spectral decomposition of

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\(^6\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
the Alm + SiIII + CIII blend indicates an SiIII/CIII flux ratio of \( \lesssim 0.3 \). This is consistent with the corresponding ratio reported in Table 2 of Bachev et al. (2004), since PG 1247+267 belongs to class B of Sulentic et al. (2002) based on the FWHM of the broad component of its H\( \beta \) line (7460 \( \pm \) 220 km s\(^{-1}\)) as measured by McIntosh et al. (1999). The integration limits adopted further reduce by a factor of \( \sim 2 \) the contribution to the computed CIII flux of SiIII, which has therefore been neglected. Similarly, the adopted continuum and integration limits should avoid the contamination of CIV flux from the HeII(1640 Å) and OIII(1663 Å) emission. The lower panel of Figure 1 shows the rms spectrum. As expected, it appears more noisy than the average spectrum (see Denney 2012). Nonetheless, in the case of the stronger line CIV, the average and rms profiles appear similar (see Section 4).

Line fluxes are computed as \( f_1 = \int_{\lambda}^{\lambda_2} (\lambda - \lambda_1) d\lambda \), where \( \lambda \) is the linear interpolation through the continua at shorter and longer wavelengths of each line, \( \lambda_{\text{short}} \) and \( \lambda_{\text{long}} \) indicated in Figure 1, and the extremes of integration \( \lambda_1 \) and \( \lambda_2 \) are chosen to optimize the \( f_1 \) signal-to-noise ratio and do not necessarily coincide with \( \lambda_{\text{short}} \) and \( \lambda_{\text{long}} \) (see Trevese et al. 2007).

The uncertainties on line fluxes are estimated by computing the flux difference \( \delta = |f_2(\lambda) - f_1(\lambda)| \) between two exposures taken at the same epoch. Since the exposure time is roughly constant at all epochs and fluxes are computed as the average between two exposures, we adopt as our uncertainty on the flux \( \sigma_f = (\delta^2)^{1/2} / 2 \), where the angular brackets indicate the average over the entire set of measurements. The fractional values of \( \sigma_f \) for continuum, CIII, and CIV fluxes are 0.008, 0.021, and 0.015, respectively. Direct photometry of the field was also obtained at most epochs to obtain an independent measure of the quasar luminosity changes relative to the reference star, and to check the stability of the reference star against other objects in the field. Typically, at each epoch, R-band photometry was obtained with exposures of 400 s at the Asiago Observatory. Photometry is also available in the R and/or V bands, from the Loiano Observatory.

From the average spectrum, we can estimate that the contribution of the CIII line to the R and V magnitudes is about 0.04 mag and 0.03 mag, respectively, while the contribution of CIV is negligible in both bands. Thus, we can use photometric data to measure continuum variations without significantly altering the continuum-line cross-correlation function. In doing this, we convert V magnitudes to R’ magnitudes assuming R’(V) \( \equiv \) V-(V-R), where the angular brackets indicate the average over those epochs when both R and V are measured. This conversion assumes that the V-R quasar color is constant. We have checked that rms color changes are of the order of 0.007 mag. Such color changes could slightly affect the amplitude of the continuum-line cross-correlation only in the case of CIII, but cannot significantly affect the estimate of the time delay. A measure of the continuum changes can also be obtained from the spectra. This has been achieved by fitting with a single straight line, \( \log F_{\text{cont}}(\lambda) = -a \log \lambda + b \), the four data points that define the local continuum (shown in Figure 1). From these fits, we have identified a conventional spectral continuum at the peak wavelength of the Bessell (1990) V band, \( F_C \equiv F_{\text{cont}}(5300 \text{ Å}) \). For the subsequent analysis (see Section 3), continuum flux changes were referred to the epoch \( t_{\text{ref}} \) (MJD = 53047.5) and expressed as magnitude changes \( \delta m_C(t_i) = 2.5 \log [F_C(t_i)/F_C(t_{\text{ref}})] \). A similar process was used for line fluxes. Continuum changes obtained from broadband photometry have been reduced to the same scale defining \( \delta R(t_i) = \Delta R(t_i) + (\delta m_C - \Delta R) \), where the average is taken over all the epochs when both photometric and spectroscopic data are available.

Table 1 reports the results. Column 1 presents the date, Column 2 presents the Modified Julian Date (MJD), Column 3 indicates the telescope, Columns 4 and 5 present the V- and R-band magnitude differences with respect to the reference star, Column 6 presents the continuum changes \( \delta R \) obtained from broadband photometry, Column 7 presents the continuum specific flux \( F_C \) at \( \lambda = 5300 \text{ Å} \), and Columns 8 and 9 present the CIII and CIV line fluxes, respectively.

Figure 2 reports the light curves in magnitude for the continuum and emission lines.

3. MEASURING THE REVERBERATION TIME LAGS

The time lag \( \tau \) of the emission line variation with respect to continuum changes is measured by the centroid of the continuum-emission line cross-correlation function, which can be computed using the discrete correlation function (DCF; Edelson & Krolik 1988) or by interpolating the light curves (Gaskell & Peterson 1987; White & Peterson 1994). Both methods provide consistent results for well-sampled light curves. In the case of poor sampling, both methods present technical problems (see the review by Peterson 1993). In particular, the DCF becomes less sensitive to real correlations. Moreover, the estimate of a confidence interval on the measured time lag, which can be obtained by the z-transform method developed by Alexander (1997), requires us to eliminate from each DCF bin all of the points corresponding to pairs of epochs having a measure in common. This causes us to lose part of the information contained in the data, and so the method may be not applicable if the total number of observations is too small.

We adopt a methodology called the Stochastic Process Estimation for AGN Reverberation (SPEAR) developed by Zu et al. (2011). The statistical basis of the method was introduced by Press et al. (1992) and Rybicki & Press (1992). A subsequent
In our analysis, for $\Psi(t)$ we assume the simple form adopted by Zu et al. (2011):

$$\Psi(t) = A/\Delta, |t - \tau_d| \leq \Delta; \quad \Psi(t) = 0 \text{ elsewhere},$$

where $A$, $\tau_d$, and $\Delta$ represent the attenuation, line-continuum lag, and the temporal width, respectively. A maximum likelihood code determines the attenuation, smoothing, and time lag parameters. The resulting emission line delay $\tau_d$ does not depend strongly on the form assumed for $\Psi(t)$ (Rybicki & Kleyna 1994). The correlation functions of the data are represented by parametric models whose parameters are also determined by likelihood maximization. This allows us to add information deduced from existing data on the statistical properties of QSO light curves. In fact, it has been shown that a damped random walk (DRW) process is a good representation of QSO variability (Kelly et al. 2009; Kozłowski et al. 2010; MacLeod et al. 2010; Zu et al. 2013b). The DRW auto-correlation function of the continuum changes $c(t)$ has the following form:

$$\langle c(t)c(t + \tau_d) \rangle = \sigma^2 \exp(-|\tau_d|/\tau_d),$$

where $\tau_d$ is a time lag, $\tau_d$ is the damping timescale, $\sigma$ is the variability amplitude, and the angular brackets indicate the ensemble average. Another important feature of the SPEAR method is that the light curves of more lines can be included in the same fitting procedure. This provides more stringent constraints that allow for a better choice among the local likelihood maxima in the parameter space.

A single fitting procedure determines the eight parameters: $\sigma$ and $\tau_d$ for the continuum, the time lags $\tau_c^{\text{CIV}}$ and $\tau_c^{\text{CII}}$, the amplitudes $A_{\text{CIV}}$ and $A_{\text{CII}}$, and the smoothing parameters $\Delta_{\text{CIV}}$ and $\Delta_{\text{CII}}$ for the two lines, respectively. SPEAR adopts a Bayesian method to determine the confidence interval in the parameter space. Once the values of the parameters maximizing the likelihood are determined, random increments obtained from prior statistical distributions are applied to all of the parameters and the likelihood is re-evaluated. Following
a Markov Chain Monte Carlo (MCMC) method (see Press et al. 2007, and references therein), the process is iterated and a posterior distribution of the acceptable parameters is produced. Figure 3 shows the distribution of points generated by 10^5 MCMC iterations in the (τ_CIV, τ_CIII) plane. Contours correspond to 68% and 95% confidence levels. The white cross indicates the median values of the marginal distributions of the two parameters.

With respect to our preliminary results (Perna et al. 2014), the present analysis differs because (1) we simultaneously fit both the CIV and CIII light curves, (2) the continuum light curve includes the available V- and R-band photometry, together with the continuum variations measured from the spectra, and (3) we have included photometric and spectroscopic data of the three most recent epochs. Considering the small number of points and the uneven sampling, with two main gaps for MJD (53900, 54500) and MJD (55000, 55600), it is worth questioning whether the likelihood maxima are real or are determined by the sampling pattern. To this end, we performed a Monte Carlo simulation, generating N = 1000 mock, uncorrelated, continuum and emission line light curves, assuming the same set of sampling epochs, rms variability amplitudes, and measurement uncertainties. We applied the SPEAR procedure to the kth set of light curves and, once σ and τ_k were fitted, we produced a likelihood “image” L_k(τ_k, Δ_k) as a function of the lag τ_k and the smoothing parameter Δ_k, (l = CIV, CIII). Then, we analyzed the sum L = Σ_k L_k, which must show the local maxima corresponding to the points (τ_k, Δ_k) where maxima occur more frequently in the simulations, and thus indicating the effect of the fixed sampling pattern. The result shows that local maxima do exist but, with respect to the case of real data, (1) they are confined to much lower values of Δ_CIV and Δ_CIII, (2) they are less pronounced, and, most important, (3) they are not located in the same position of the (τ_CIV - τ_CIII) plane where they occur in the case of real data.

We can conclude that it is very unlikely that the local maxima related to the sampling pattern produce the maxima obtained in the case of the measured light curves. Thus, we assume this result as first evidence that the values of τ_CIV and τ_CIII for PG 1247+267 are due to real echo lags.

We can compare them with the few corresponding RM results available in the literature. Measures of both the CIV and CIII time lags from RM exist for three Seyfert nuclei: NGC 5548 (Peterson & Wandel 1999), NGC 3783 (Onken & Peterson 2002), and NGC 4151 (Metzroth et al. 2006, and references therein), which are all less luminous than L_\lambda(1350 Å) ~ 4 × 10^{43} erg s^{-1}. On average, the ratio of the time lags of these two lines is τ_CIII/τ_CIV ~ 2. While there is no reason to expect that a QSO, 10^4 times more luminous, should show approximately the same ratio, it is interesting to note that in the case of PG 1247+267, we obtain τ_CIV/τ_CIII ~ 2, i.e., the typical distance from the continuum source of the emission region of the semi-forbidden CIII line is about twice the distance of the CIV emission region. The situation is summarized in Figure 5 where we also report the relevant time lags for the QSO 2237+0305 as we deduced from the results of Sluse et al. (2011), who estimate the size of the CIV and CIII emission regions based on microlensing. The corresponding point looks roughly consistent with the general trend, despite the relevant sizes being of the order of 100 times larger than those of Seyfert galaxies. A straight line fit to the data points in Figure 5, log τ_CIII = a log τ_CIV + b, gives a = 0.83 ± 0.21 and b = 0.43 ± 0.19. A fit with fixed unitary slope gives τ_CIII/τ_CIV = 1.8 ± 0.5. The very existence of this relation can be taken as a second suggestion that we are probably measuring real reverberation time lags. This result would mean that the ionization stratification in Seyfert nuclei and luminous quasars is similar.
Figure 5. Reverberation time lags $\tau_{\text{obs}}$ vs. $\tau_{\text{em}}$ for NGC 5548, NGC 3783, NGC 4151, and PG 1247+267 (our estimate). The emission region sizes (Sluse et al. 2011), converted to time lags, are also reported for the quasar QSO 2237+0305. Straight lines represent linear fits with errors on both variables: the continuous line with two free parameters and the dotted line with fixed unitary slope.

Figure 6. Size–luminosity relation obtained from the C iv emission line and UV continuum. Open circles: data from Peterson et al. (2005, 2006) plus the values for S5 0836+71 from Kaspi et al. (2007). Filled circle: our result for PG 1247+267. The dotted line represents the linear fit obtained by Kaspi et al. (2007) using the FITEXY method (Press et al. 1992).
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Table 2  
Reverberation Results for PG 1247+267  

| Emission line | $t_f^*$ | FWHM$_\text{mean}$ | $\sigma_{\text{mean}}$ | FWHM$_\text{rms}$ | $\sigma_{\text{rms}}$ | $\tau_{\text{rms}}$ | $\Delta$ | $V_{\text{rms}}$ | $C$ | $\lambda L_{\lambda}$ | $\lambda_{1549}$ | $\lambda_{1909}$ | $\lambda_{1350}$ | $\lambda_{188}$ | $\lambda_{430}$ | $\lambda_{540}$ | $\lambda_{1819}$ | $\lambda_{1900}$ |
|--------------|---------|-------------------|----------------|---------------|----------------|-------------|--------|----------------|-----|----------------|----------|-----------|--------------|------------|-----------|-------------|------------|----------|-------------|----------|
| C IV $\lambda$ 1549 | 142 $^{+50}_{-25}$ | 4939 ± 117 | 2673 ± 20 | 4568 ± 1338 | 2104 ± 540 | 0.5 | 1.8 | 21 | 2.4 | 1.1 | 1338 2104 $^{+63 2365}_{-540}$ |
| C IV $\lambda$ 1909 | 273 $^{+60}_{-21}$ | 5224 ± 63 | 2365 ± 15 | 4752 ± 1156 | 1899 ± 713 |

Note. *In the rest frame.

We stress that since the distribution of $\Delta V^2$ and $t_f$ is asymmetric, some care is needed when deriving the fiducial mass values and the relevant confidence intervals. For this purpose, we computed a probability distribution of the virial product, as a function of $\Delta V^2$ and $t_f$, by multiplying the posterior distribution of $t_f$ (see Figure 4) and the statistical distribution of $\Delta V^2$ obtained using the bootstrap method. From this, we derived a posterior distribution of the black hole mass. In addition to the modal mass value $M_{\text{BH}}$, in Table 3 we report the value computed as the centroid of the posterior distribution, together with the asymmetric errors at the 68% confidence level. Hereafter, we will use $M_{\text{BH}} = 8.3_{-2.7}^{+3.4} \times 10^9 M_\odot$ as our best estimate of the virial mass (in bold face in Table 3). The corresponding mass values obtained from C III are also reported in Table 3.

We can compare our result with the summary of BH masses, known from RM, versus $\lambda L_{\lambda}(1350 \text{ Å})$, shown in Figure 5 of Chelouche et al. (2012). Based on this comparison, it appears that the new point that we are adding at the highest luminosity corresponds to a mass which is roughly a factor of 20 smaller with respect to the extrapolation of the general trend, which would predict a mass of the order of $2 \times 10^9 M_\odot$. The scatter of points around the $M_{\text{BH}}-\lambda L_{\lambda}(1350 \text{ Å})$ relation is partly intrinsic, due to the fact that different AGNs may be emitting at different Eddington ratios, and partly caused by the uncertainty on the $f$ factor appropriate for individual objects. Thus, a deviation from the average scaling relation of a factor of~20 is not surprising. However, it does deserve further discussion.

5. DISCUSSION AND SUMMARY

The number of spectral observations is still small and deriving any conclusion requires caution. However, three independent circumstances suggest that we are probably measuring real reverberation time lags: (1) although it is reasonable to expect that the likelihood maxima might be determined by the uneven temporal sampling, Monte Carlo simulations with mock random light curves and the same sampling pattern do not produce likelihood maxima in the same region of the parameters space; (2) the measured C IV and C III reverberation time lag appears to be consistent with the $\tau_{\text{CIV}}-\tau_{\text{CIII}}$ relation derived from the data available in the literature; and (3) the virial products for the C IV and C III lines appear to be consistent with the same black hole mass.

Thus, assuming that the measured $\tau_{\text{CIII}}$ and $\tau_{\text{CIV}}$ are real, we can derive some tentative conclusions.

The fact that the approximate relation $\tau_{\text{CIII}} \sim 2 \tau_{\text{CIV}}$ (see Figure 5) extends for objects with a luminosity of $\lambda L_{\lambda}(1350 \text{ Å})$ from $\approx 4 \times 10^3$ to $\approx 4 \times 10^8 \text{ erg s}^{-1}$, if confirmed, would be the first direct evidence that the ionization stratification in luminous QSOs is similar to that found in Seyfert galaxies.

The relatively small $\tau_{\text{CIV}}$, about 0.3 of the value expected from the extrapolation of the $\tau_f-L$ relation, tends to produce a small virial mass. The problem is made more severe by the
small value of the line widths, roughly two-thirds of that of S5 0836+071, which is 3.5 times less luminous. This appears clearly when we compute the Eddington ratio $L_{\text{bol}}/L_{\text{Edd}}$, which contains a further uncertainty deriving from the estimate of the bolometric correction. Kaspi et al. (2007) adopt the bolometric correction of Marconi et al. (2004) (Equation (21)) which refers to the luminosity $\nu_{B}L_{\nu,B}$. For PG 1247+267, we obtain $\nu_{B}L_{\nu,B} = 2.0 \times 10^{47}$ erg s$^{-1}$, interpolating between the values of $\lambda L_{\lambda}(2500 \text{ Å})$ and $\lambda L_{\lambda}(5100 \text{ Å})$ provided by Krawczynk et al. (2013). The resulting correction is $L_{\text{bol}}/\nu_{B}L_{\nu,B} = 5.28$, leading to $L_{\text{bol}} = 1.06 \times 10^{48}$ erg s$^{-1}$ and $L_{\text{bol}}/L_{\text{Edd}} = 9.8$ (after a small correction for the different cosmology we adopt). A similar result, $L_{\text{bol}}/L_{\text{Edd}} \sim 10.4$, is found after adopting the bolometric correction of $L(1\mu - 2\text{keV})/\nu L_{\nu}(2500 \text{ Å}) = 3.5$ with log $\nu L_{\nu}(2500 \text{ Å}) = 47.50$ from Krawczynk et al. (2013).

We stress that this large Eddington ratio is due only in part to the small size of the BLR. In fact, even the SE mass estimate, which is independent of reverberation lag, for PG 1247+267 produces an Eddington ratio in the range 1.2–3, depending on the use of the line shape correction (Denney 2012) and the different choices of bolometric correction.

As discussed in the previous section, one possible origin of a line width that is too small may be the presence of a narrow emission line component or the contribution of a possibly non-variable and non-virial wind component. This suggests using the rms spectrum. Besides this, the orbits of BLR clouds are unlikely to be randomly oriented, as suggested by various evidence reviewed by Gaskell (2009), and sources viewed at a low inclination angle (nearly face-on) show a small FWHM, leading to a systematic underestimation of the black hole mass by a factor of up to ~10 (Marziani & Sulentic 2012).

For five Seyfert nuclei, Pancoast et al. (2013) computed line profile models that depend on the opening angle of the cloud distribution for different values of the inclination angle with respect to the axis of the accretion disk. The relevant virial factor $f$, to be applied when using $\sigma_{i}$ from the rms spectra, can be as high as 50 for an inclination angle of 8 degrees. Thus, a plausible value of the virial factor $f$ could easily bring the Eddington ratio toward more common values, without, however, explaining the relatively small reverberation time lag.

The effects of orientation on the characteristics of the C iv line have been investigated by Runnoe et al. (2014). By comparison with their Figure 3, the small amplitude relative to Si iv and the narrow line width found in the spectrum of PG 1247+267 in fact suggest a small inclination angle, supporting a high-$f$ value. However, more quantitative evidence would require, a dynamical modeling of the type presented by Pancoast et al. (2013), and a comparison with velocity-resolved RM, which is not feasible with our present data.

A different, and apparently trivial, explanation for the high Eddington ratio may be an overestimate of the luminosity caused by gravitational lensing. At the same time, allowing for magnification would justify the apparently small BLR size. Moreover, we suggest taking into account two other concurrent clues. The first clue concerns the negative correlation between $\alpha_{\text{ox}} = 0.384 \log L_{\nu}(2\text{keV})/L_{\nu}(2500 \text{ Å})$ and $L_{\nu}(2500 \text{ Å})$ found in statistical samples of QSOs/AGNs. With respect to this relation, PG 1247+267, with $\alpha_{\text{ox}} = -1.69$ and $L_{\nu}(2500 \text{ Å}) = 2.5 \times 10^{47}$ erg s$^{-1}$ (Shemmer et al. 2014), deviates from the general trend by an apparently significant amount, despite the relatively large spread around the average relation. Allowing for a gravitational amplification would not change $\alpha_{\text{ox}}$, but changing $L_{\nu}(2500 \text{ Å})$ could make this object fully consistent with the general distribution, as it occurs in the case of the confirmed lensed QSO 2XMM J091301.0+525929 (see Vagnetti et al. 2010, and references therein). The second clue concerns the Baldwin (1977) effect. With respect to the average negative correlation between the C iv equivalent width (EW) and $\lambda L_{\lambda}(1350 \text{ Å})$ (Bian et al. 2012), PG 1247+267, with EW = 39.5 Å (Shen et al. 2011), is again deviant and would be brought to full consistency by allowing for gravitational lensing. An amplification of about 10 at the same time would (1) account for both these effects, (2) bring the Eddington ratio to ~1, and (3) make this object less luminous than S5 0836+071 and consistent with the $\tau_{1}L_{1}$ relation.

A candidate damped Ly$\alpha$ system (DLA) at $z = 1.223$ in the spectrum of PG 1247+267 was analyzed by Pettini et al. (1999). Although Turnshek & Rao (2002) consider the column density to be too low to classify this absorption system as a DLA, according to the conventional threshold $N_H = 2 \times 10^{20} \text{cm}^{-2}$, it could be associated with a foreground lensing galaxy. Of course, this does not exclude the fact that anisotropic (close to face-on) emission, possible intrinsic super-Eddington emission, and gravitational lensing occur at the same time. This suggests that we need to further observe the spectral variability to perform velocity resolved RM, and also to investigate lensing evidences. Finally, we note that PG 1247+267 is the fifth most luminous of ~100,000 QSOs in the Shen et al. (2011) catalog. Among the most luminous objects, the fraction of lensed QSOs may be high enough to bias the SE mass estimates and the studies of the evolution of both the mass function and the Eddington ratio distribution in cosmic time.

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