A PHOTO-IONIZATION METHOD FOR BLACK HOLE MASS ESTIMATION IN QUASARS

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Abstract. Determining the masses of the central compact object believed to power all active galactic nuclei is relevant to our understanding of their evolution and of their inner workings. Keys to present-day mass estimates are: (1) the assumption of line broadening due to virial motion of the emitting gas, (2) an estimate of the distance of broad-line emitting gas from the central compact object, and (3) a measure of the AGN luminosity. We discuss the merits and the limitations of an alternative method based on estimates of physical conditions in the broad line emitting region derived from an appropriate multi-component analysis of emission line profiles. This ‘photo-ionization method’, applied to UV intermediate-ionization lines appears to be promising for at least a sizable population of high-z quasars.

Key words: quasars: general, emission lines, individual: SDSS J120144.36+011611.6

1. INTRODUCTION

The black hole mass ($M_{BH}$) is a fundamental parameter that is related to the evolutionary stage and the accretion process occurring within quasars. Estimates of the black hole mass allows us to assess the effect of gravitational forces on the dynamics of the region surrounding the black hole. The power output of quasars is directly proportional to $M_{BH}$ if, as widely believed, the power source involves release of gravitational energy through accretion processes. It is currently debated how the evolution of quasar energetics might affect the development and structure of the host galaxy, as well as larger scale structure formation and, at very high redshifts, re-ionization of the Universe.

2. VIRIAL MASSES

Black hole masses in quasars are estimated from motions of gas in the vicinity of the central continuum source. If one considers the prominent broad emission lines typically observed in quasar spectra, the virial $M_{BH}$ can be written as:
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\[ M_{\text{BH}} = f \frac{r_{\text{BLR}}(\delta v)^2}{G}, \]  

where \( r_{\text{BLR}} \) is the distance of the broad line emitting region (BLR) from the central continuum source, \( G \) the gravitational constant, \( \delta v \) a measurement of the radial velocity dispersion, and \( f \) a parameter dependent on physics and geometry.

Equation 1 is deceptively simple. If the virial assumption is valid, the BLR dynamics should be dominated by the gravity of a central massive object (and this is certainly true if the 'object' is a black hole). The determination of the term \( \delta v \) rests on the assumption that line broadening is due to Doppler displacement produced by motions of the emitting gas. Apart from these underlying assumptions, every factor appearing in Eq. 1 is problematic: \( r_{\text{BLR}} \) since the BLR is not spatially resolved; \( \delta v \) because one must determine which line or line component (if any) is broadened by emitting gas whose motion is at least approximately virialized. The geometry factor represents a special challenge. Even if it is \( \sim 1 \), radiation pressure forces and orientation effects can make \( f \) strongly different from object to object (Netzer & Marziani 2010).

This paper focuses on a method for estimating \( r_{\text{BLR}} \).

3. LINE PROFILES

Emission line spectroscopy points toward three different components in broad line profiles (see Marziani et al. 2010) which can be described as follows:

1. A broad component (BC) showing a roughly symmetric profile with FWHM in the range 1000–5000 km s\(^{-1}\). It is consistent with the component identified by Matsuoka et al. (2008) and is approximated by the reverberating component revealed in rms spectra that are computed when multi-epoch observations are available (Peterson et al. 2004). This broad component dominates low-ionization lines (LILs) in Pop. A sources while it becomes less prominent in Pop. B. Pop. A line profiles are best modeled by a Lorentzian function while Pop. B profiles are better described by a Gaussian (Marziani et al. 2003).

2. A very broad component (VBC), best seen in LILs (e.g. H\(\beta\)) of most Pop. B sources (it is absent in Pop. A profiles). The VBC can be modeled as a Gaussian (FWHM \( \sim 10000 \) km s\(^{-1}\)) usually with a significant redshift (\( \Delta v \sim 1000–2000 \) km s\(^{-1}\)). It can be called a defining property of Pop. B sources.

3. A blue-shifted broad component most effectively defined as the residual emission in C IV \( \lambda 1549 \) after subtraction of a scaled H\(\beta\) broad component (Marziani et al. 2010). The blue-shifted component is most prominent in C IV \( \lambda 1549 \) and Ly\(\alpha\) but only in Pop. A sources.

It is clear that the BC is the only component that might be useful as a virial estimator. The situation is easier for Pop. A sources where LILs are dominated by the usually unshifted (wrt rest frame) BC component. The situation is more tricky for Pop. B sources where the BC can show significant shifts. In addition, single-epoch FWHM measures are not necessarily the best estimators of gas velocity dispersion (Peterson et al. 2004). At the very least, line profiles in Pop. B sources must be corrected for the VBC however FWHM is estimated.

3. CURRENT RESULTS

The remaining part of this contribution will focus on estimation of \( r_{\text{BLR}} \) following a method based on modeling of physical conditions in the line emitting
gas. $r_{\text{BLR}}$ is presently known for about 50 AGN using a ‘primary’ method (reverberation mapping) applied to the H I H$\beta$ line. The cross correlation function between continuum and emission line light curves measures the time lag $\tau_L$ for emission line response to a continuum change. The time lag due to the light travel time needed by continuum photons to reach the broad line region yields an estimate of $r_{\text{BLR}} \approx c\tau_L$. Reverberation-derived radii correlate with source luminosity: $r_{\text{BLR}} \propto L_\lambda^a$, where $a = 0.5-0.7$ (most likely $a \approx 0.52$; Kaspi et al. 2005; Bentz et al. 2009). We can therefore define the black hole mass as: $M_{\text{BH}} \propto \text{FWHM(BC)}^2 (\lambda L_\lambda)^a$, where $L_\lambda$ is the specific luminosity at $\lambda$ in units of erg$^{-1}$ Å$^{-1}$. This ‘secondary’ method can greatly expand the small sample of reverberation-derived masses by using single epoch FWHM measures from spectra calibrated in physical units that also allow estimation of source luminosity.

4. A PHOTO-IONIZATION METHOD

Emission lines and line ratios are used in diagnostic diagrams to estimate temperature and electron density in galactic and extragalactic photo-ionized regions. This method has been successfully applied to H II regions and to the narrow line region (NLR) in AGNs. Application to the broad line quasars has proved much more difficult.

The physical conditions of photo-ionized gas can be described by the hydrogen numerical density $n_H$ or electron density, the hydrogen column density $N_H$, the metallicity $Z$, the shape of the ionizing continuum, and the ionization parameter $U$. The latter represents the dimensionless ratio of the number of ionizing photons and the total hydrogen density. Both $U$ and $n_H$ are related through the equation

$$U = \frac{\int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu}{4\pi n_H c r^2},$$

where $L_\nu$ is the specific luminosity per unit frequency, $h$ is the Planck constant, $\nu_0$ the Rydberg frequency, $c$ the speed of light, and $r$ can be interpreted as the distance between the central source of ionizing radiation and the line emitting region. If we know the product of $n_H$ and $U$, we can estimate the radius $r$ of the BLR from Eq. 2:

$$r_{\text{BLR}} = \frac{1}{(4\pi c)^{\frac{1}{2}}} \left( \frac{U n_H}{\text{const. diagnostics}} \right)^{-\frac{1}{2}} \left( \frac{\int_{\nu_0}^{\infty} L_\nu d\nu}{\int_{\nu_0}^{\infty} \frac{h\nu}{L_\nu} d\nu} \right)^{\frac{1}{2}},$$

where we have grouped the relevant factors for estimating $r_{\text{BLR}}$.

The dependence of $U$ on $r_{\text{BLR}}$ was used by Padovani & Rafanelli (1988) to compute central black hole masses assuming a plausible average value of the product $n_e U \approx 10^{9.8}$ cm$^{-3}$. The average $n_e U$ was derived considering sources for which $r_{\text{BLR}}$ was available from reverberation mapping, and then used to compute $M_{\text{BH}}$ for a much larger sample of Seyfert 1 galaxies and low-$z$ quasars (Padovani & Rafanelli 1988; Padovani, Burg & Edelson 1990). Multi-frequency data were used to define the shape of the ionizing continuum for each individual source. Wandel, Peterson & Malkan (1999) compared photo-ionization method results with those
obtained via reverberation mapping and found a very good correlation between the two mass estimates.

6. THE DIAGNOSTICS

6.1. Diagnostic ratios

Line ratios like C III λ1909 / Si III λ1892 and Al III λ1860 / Si III λ1892 are useful diagnostics in a range of density that depends on their transition probabilities (e.g., Feldman et al. 1992). Emission lines originating from forbidden or semi-forbidden transitions become collisionally quenched above the critical density and, hence, weaker than lines for which collisional effects are still negligible. C III λ1909 / Si III λ1892 is suitable as a diagnostic for $n_e < 10^{11}$ cm$^{-3}$. The Al III λ1860 / Si III λ1892 ratio is well suited to sample the density range $10^{11} - 10^{13}$ cm$^{-3}$. This corresponds to the densest, low ionization emitting regions likely associated with the production of Fe II.

The ratios Si II λ1814 / Si III λ1892 and Si IV λ1397 / Si III λ1892 are independent of metallicity and sensitive to ionization. Conversely, the ratio C IV λ1549 / Si IV λ1397 is mainly sensitive to metallicity. In addition the ratios C IV λ1549 / Al III λ1860 and C IV λ1549 / Si III λ1892 provide information about ionization that is not independent of metallicity. Even if some ratios are in principle nonessential, the difficulty of measuring some lines (e.g. due to blending or faintness) make the case for cautious use of redundant information. Computation of constant value contours for these diagnostic ratios in the $U$ vs. $n_H$ plane shows convergence towards a low ionization plus high density range.

6.2. Photo-ionization calculations

Diagnostics of density and ionization are provided by emission line ratios. We computed a multidimensional grid of CLOUDY (Ferland et al. 1998) simulations (see also Korista et al. 1997) in order to derive $U$ and $n_H$. Simulations span the density range $7.00 \leq \log n_H \leq 14.00$, and $-4.50 \leq \log U \leq 0.00$ (in intervals of 0.25) assuming $N_e = 10^{23}$ cm$^{-2}$. Each simulation was computed for a fixed ionization parameter and density assuming plane parallel geometry. Two alternative continua were used in the photo-ionization calculations: (1) the standard AGN continuum of CLOUDY and (2) the low-$z$ quasar continuum of Laor et al. (1997). Computed line ratios are almost identical for fixed ($U$, $n_H$); however, the ionizing luminosity differs by more than a factor of 2 for a fixed specific continuum luminosity. The 2D grid of simulations was repeated with varying metallicity. Three cases were considered: solar, 5× solar, 5× solar with silicon and aluminum enhancement.

6.3. Supersolar metallicity

Chemical abundances may be well 5–10× solar (Dhanda et al. 2007) with $Z \approx 5Z_\odot$ reported as typical for high $z$ quasars (Ferland et al. 1996). The E1 sequence is likely a sequence of ionization in the sense of a steady decrease in prominence of the low-ionization BC towards Population B. Metal-enrichment might also play a role especially for the most extreme Pop. A sources, i.e., those in bin A3 and higher (Sulentic et al. 2001). The lines employed in the present study come from carbon, silicon and aluminum which could be depleted in the gas if
Fig. 1. The C IV λ1549 (left) and λ1900 (right) spectral regions of the NLSy1-like object SDSS J120144.36+011611.6. The major constituents of the blend are identified. The thick grey line shows the scaled template Fe II emission; the thin grey line is for Fe III. The shaded area corresponds to the C III] λ1909 and Fe III λ1914 lines whose intensity is ill-determined.

dust grains are formed (e.g., Mathis 1990). This is not the case of the BLR since the gas is probably too hot to contain significant amount of dust. We note also that the C IV λ1549 / Si III] λ1892 and C IV λ1549 / Al III λ1860 usually give results that are in perfect agreement in the plane \((n_H, U)\) justifying the assumption that the relative abundances of Al and Si remain constant if metallicity variations are present. We considered an overabundance of Si and Al with respect to carbon by a factor of 3, again with \(Z = 5Z_\odot\). This condition comes from the chemical composition of gas returned to the interstellar medium by type II SNæ produced by the evolution of a top-loaded stellar population.

7. THE TARGETS

The Narrow-Line Seyfert 1 (NLSy1) I Zw 1 is known to be a rather extreme source in the E1 sequence. It shows strong Fe II and Fe III, prominent Al III and Si III emission. It is an example of the A3 spectral type for which the median 1900 Å blend is shown in Fig. 3 of Bachev et al. (2004). Sources equivalent to I Zw 1 are also definitely present at intermediate to high redshift. If we perform a search in the SDSS DR7 for quasars in the redshift range \(2 < z < 3\), where both C IV λ1549 and the λ1900 blend are observed at optical wavelengths, we find more than 200 candidates with spectra resembling that of I Zw 1.

8. RESULTS ON SDSS J1201+0116

We describe here our analysis of one source SDSS J120144.36+011611.6 (Figure 1) that appears to be a high-z analogue of I Zw 1. It shows broader lines presumably because the lower FWHM limit for NLSy1 and Pop. A sources is luminosity dependent (see Netzer & Trakhtenbrot 2007 and Marziani et al. 2009). Since the narrowest FWHM sources at any redshift are Pop. A we assume that the BC profile is Lorentzian. We show fits to C IV λ1549 and the λ1900 blend in Figure 1.
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Fig. 2. Constant value contours for several diagnostic ratios in the ionization parameter versus density plane computed from the spectrum of J120144.36+011611.6. Left: solar metallicity; right: 5 times solar metallicity and Si and Al enrichment. The uncertainty band associated to the ratio Si\textsc{ii} λ1814 / Si\textsc{iii} λ1892 is shown on a shade of grey.

The contributions of C\textsc{iii} λ1909 and Fe\textsc{iii} λ1914 are shaded because they cannot be independently measured. We think that the most likely condition involves even fainter C\textsc{iii} λ1909 and stronger Fe\textsc{iii} λ1914 since the latter line can be enhanced by Ly\textalpha pumping. The multicomponent fits allow us to isolate contribution of C\textsc{iv} λ1549 BC, Al\textsc{iii} λ1860, Si\textsc{iii} λ1892, Si\textsc{iv} λ1397 and Si\textsc{ii} λ1814 in order to compute the diagnostic ratios described above. Figure 2 shows the constant value contours of the measured diagnostic ratios in the ionization parameter vs. density plane computed from the CLOUDY simulation. The convergence is fair in the case of solar metallicity while it is much improved if $Z = 5Z_\odot$ with Si and Al enhancement is considered. In this case (and whenever C\textsc{iii} λ1909 appears to be negligible) it is possible to derive independent estimates of density and ionization parameter, and to constrain metallicity.

9. A TENTATIVE EXTENSION OF THE METHOD

The presence of significant C\textsc{iii} λ1909 emission complicates the interpretation. The photoionization solution for the BC suggests very high density where no C\textsc{iii} λ1909 emission would be expected. Whenever C\textsc{iii} λ1909 is observed we need to reverse the question and ask: how much does C\textsc{iii} λ1909 emitting gas contribute to the lines used for diagnostic ratios? At least among Pop. A2 and A3 sources it is not obvious that the profiles of C\textsc{iii} λ1909 and Si\textsc{iii} λ1892 are the same. The C\textsc{iii} λ1909 profile may be narrower (as found for SDSS J1201+0116). If C\textsc{iii} λ1909 is formed in gas of similar ionization level, the much lower critical density implies formation at larger radii than the other lines.

In order to estimate the relative contribution of C\textsc{iii} λ1909 emitting gas to Si\textsc{iii} λ1892 and C\textsc{iv} λ1549 we can consider that Si\textsc{iii} λ1892 is strong when Al\textsc{iii} λ1860 is strong, and that the Si\textsc{iii} λ1892 / C\textsc{iii} λ1909 ratio is lower when C\textsc{iii} λ1909 is strong (Baldwin et al. 1995; Bachev et al. 2004). These trends suggest that most Si\textsc{iii} λ1892 is emitted in the same region as Al\textsc{iii} λ1860. A correction to the intensity of the diagnostic lines allows one to remove the contribution to their fluxes due to the lower density gas emitting C\textsc{iii} λ1909.
The correction is expected not to be dominant unless C III] $\lambda$1909 is more intense than Si III] $\lambda$1892.

10. THE MASSES

10.1. The reverberation mapped sample

We have applied the photoionization method to the sample of sources for which $r_{\text{BLR}}$ has been determined with reverberation mapping. A preliminary analysis indicates that the agreement of our $r_{\text{BLR}}$ estimates with the reverberation values (Bentz et al. 2009) is better than the agreement resulting from values estimated using $r_{\text{BLR}}$ vs. $L$ correlation.

10.2. A high-$z$, high luminosity pilot sample

We compare masses obtained using our photoionization method with those of Vestergaard & Peterson (2006) who used an $r_{\text{BLR}}$ vs. $L$ relationship based on the UV continuum. At first we considered a pilot sample of 9 $z \approx 3$ quasars (Figure 3). VLT-FORS spectra provided a rest frame range covering all diagnostic lines considered in this study with high $S/N$ (Negrete 2011). The masses agree within less than 1σ uncertainty in the luminosity correlation (0.33). There is a small systematic offset of 0.17 ± 0.10 if uncorrected ratios are used. After correction the systematic offset is reduced to 0.13 ± 0.12. Even if the estimated correction is an upper limit, the effect on mass values is relatively small.

10.3. Sources of error and concern

The photoionization method provides an estimate of $r_{\text{BLR}}$; derived masses still suffer from several problems associated with $f$ and with the uncertainty in the estimate of virial broadening. The method relies on the fundamental assumptions of photoionization and spherical symmetry. It also assumes one density and one ionization parameter which is clearly an oversimplification. Another problem is that the continuum shape is not well constrained for high redshift quasars. Mea-
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surement errors are still limiting the accuracy of $r_{BLR}$ estimates. They can be improved using data of higher dispersion and $S/N$.

11. CONCLUSION

Our results indicate that the $r_{BLR}$ vs. $L$ relation can be extended to high redshift sources (or at least until $z \approx 3$) if the FWHM of the core broad line component (BC) can be determined and measured. The described photoionization method: (1) works best for NLSy1-like sources at high redshift; (2) allows determination of density, ionization and metallicity; (3) works for other quasars if only the product $(nH U)$ is needed; (3) yields lower uncertainty than the method based on the $r_{BLR}$ vs. $L$ correlation; (4) requires high $S/N$ and moderate dispersion but in principle can be applied to very high $z$ (> 6.5) with IR spectrometers.

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