Photoionization Estimates of Broad Line Region Size in Active Galactic Nuclei

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ABSTRACT

We present a method to determine the distance of the Broad Line Region (BLR) from the central continuum source in type-1 AGNs. Our method is based on the determination of the physical conditions in the BLR under the assumption that the line emitting gas is photoionized by the central continuum source. We derive "diagnostic" intensity ratios that involve UV lines Al IIIλ1860, Si IIIλ]1892 and C IVλ1549. Diagnostic ratios allow us to compute the product of ionization parameter and hydrogen number density, and hence the BLR radius from the definition of the ionization parameter itself. We compare our determinations of the BLR radius with the ones independently obtained from reverberation mapping, in order to test the accuracy of our method. We also compare black hole masses obtained with the photoionization method to the ones derived from widely-applied correlations between mass, line broadening and luminosity.

Introduction

A major challenge in the study of quasars involves estimation the distance of the BLR r_{BLR} from the central continuum source. The most direct method for estimating r_{BLR} is through reverberation mapping (RM; e.g. Peterson 1998). This technique measures the time delay τ in the response of the broad emission lines to changes in the ionizing continuum:

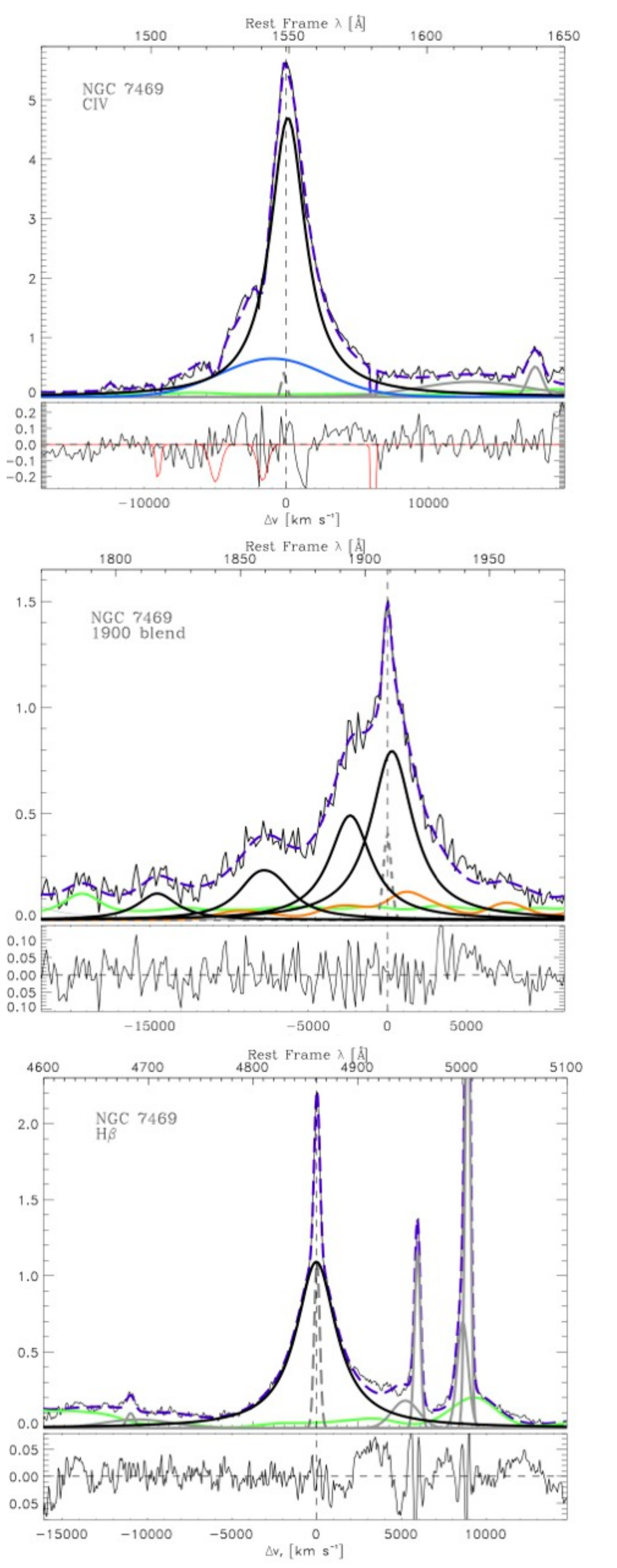
$$r_{BLR} = c \cdot \tau$$

where c is the speed of light. RM requires a significant observational effort and have been obtained for only ≈ 60 nearby objects (z < 0.4; e.g. Denney et al. 2010, Bentz et al. 2013).
In this work **we use a sub-sample of 13** RM objects to estimate r_{BLR} with an independent method based on the derivation of the ionization photon flux Un_H, the product ionization parameter U and hydrogen density. The integral represents the number of ionizing photons.

$$r_{\rm BLR} = \left(\frac{\int_{\nu_0}^{\infty} \frac{L_\nu d\nu}{h\nu}}{4\pi c \mathbf{U n_H}} \right)^{\frac{1}{2}}$$

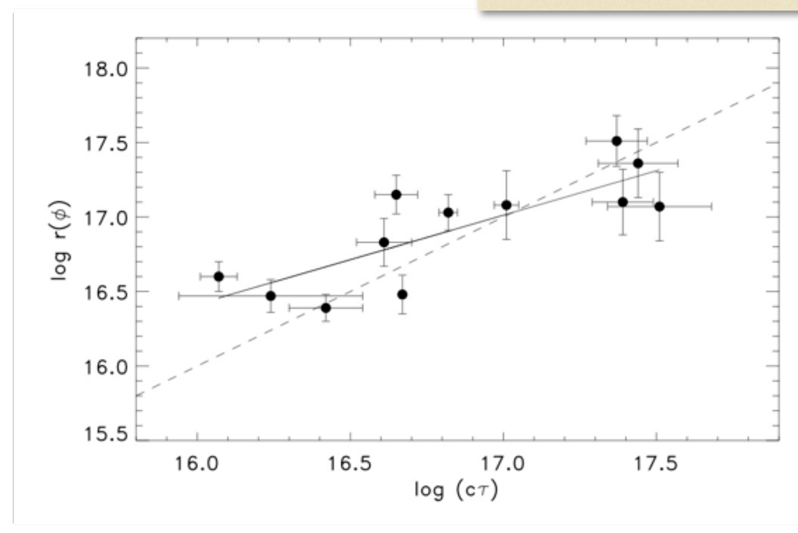
Using diagnostic line ratios **we can estimate the product $n_H U$ and determine r_{BLR} and M_{BH}**. Determination of both n_H and U *separately* has proved possible only for relatively rare, extreme sources (Negrete et al. 2012).

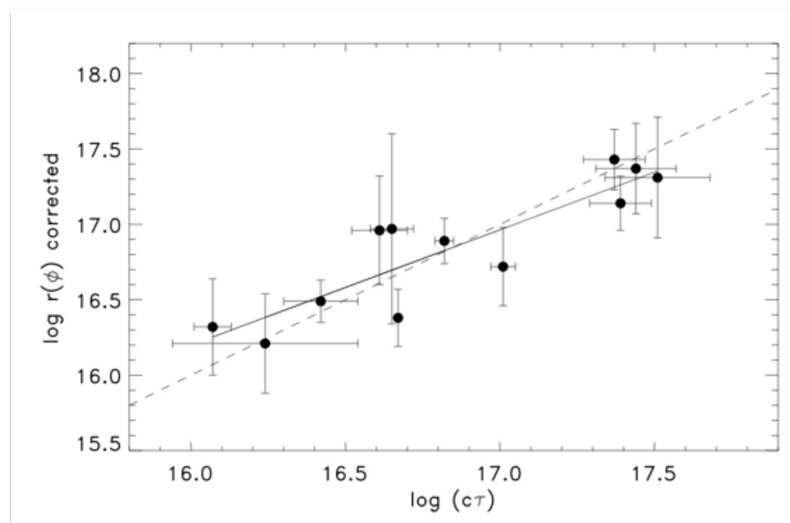
Interpretation of Line Profiles



We apply a multi-component profile decomposition using **iraf task specfit** in order to extract:
1) a relatively **unshifted, symmetric broad component (BC)** representative gas whose broadening is assumed to arise in a virial velocity field. We isolate the BC from
2) a **blueshifted component** associated with outflow emission and
3) a **very-broad component** whose strength relative to the BC is set by an inflection observed in the Hβ profile.
All BCs were assumed to have the same width of Hβ, leaving only their intensities as free parameters. **The figure above** shows an example of line deblending.

BLR Radius and Black Hole Mass





The RM sample has the advantage that r_{BLR} is independently known from reverberation. The $n_H U$ product is estimated from diagnostic line ratios as described in the panel aside.
In the figure on the left we show a comparison between our $r_{BLR\phi}$ and the RM size ($c\tau$). The relation is given by

$$\log c\tau \approx (1.16 \pm 0.07) \log r_{BLR\phi} - (2.74 \pm 0.40)$$

with a Pearson correlation coefficient of R ≈0.82 and an rms≈0.30 dex.

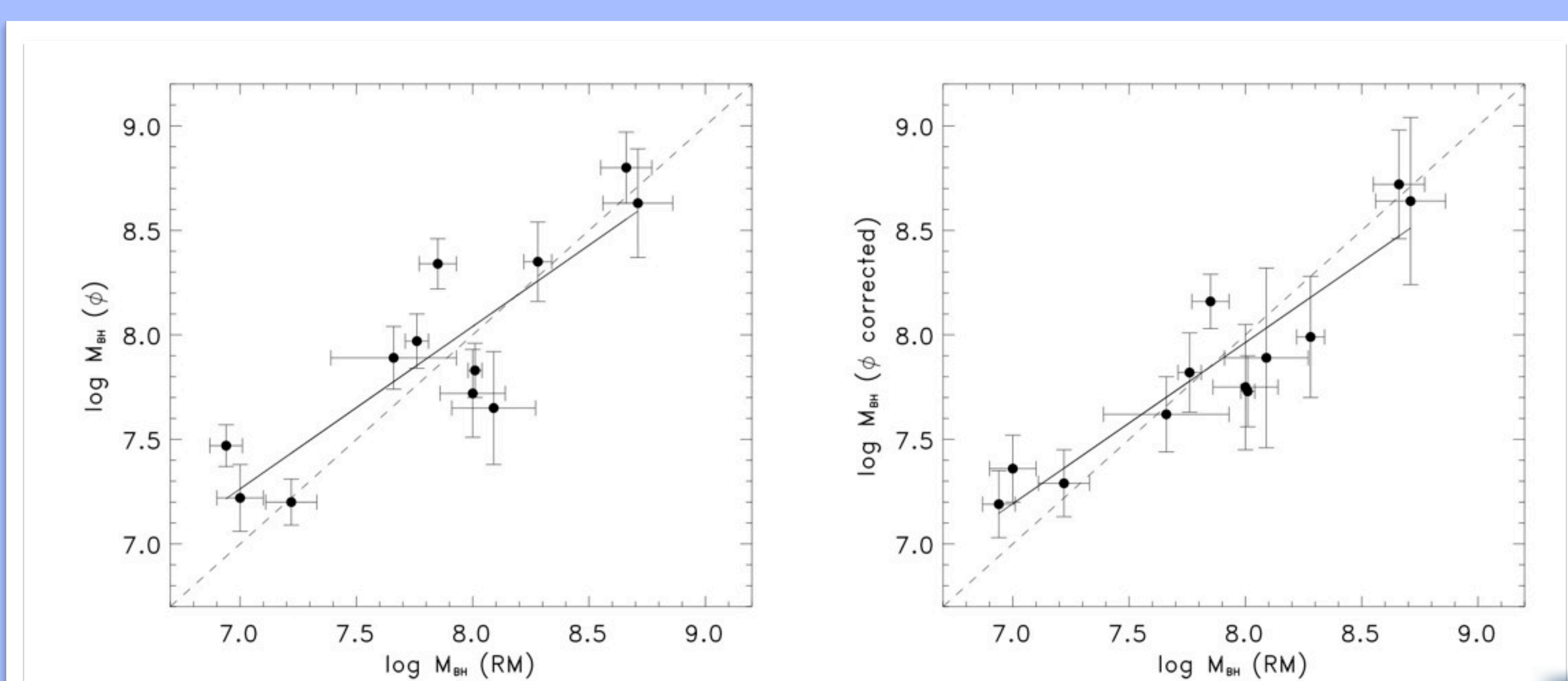
The correlation between $r_{BLR\phi}$ and $c\tau$, after an empirical correction meant to account for low density gas (as described in the bottom panel) is

$$\log r_{BLR\phi,corr} \approx (0.77 \pm 0.14) \log c\tau + (3.94 \pm 0.75)$$

with a scatter of ≈ 0.23 dex and a correlation coefficient of 0.89. **The photoionization method yields values that are statistically undistinguishable in all cases save 2, with an accuracy comparable to the luminosity correlation**. Values of $r_{BLR\phi}$ can be made somewhat **more accurate if an empirical correction that accounts for the density/ionization stratification of the BLR is applied**.
Knowing r_{BLR} enables us to estimate the black hole mass (M_{BH}) assuming virial motions of the gas:

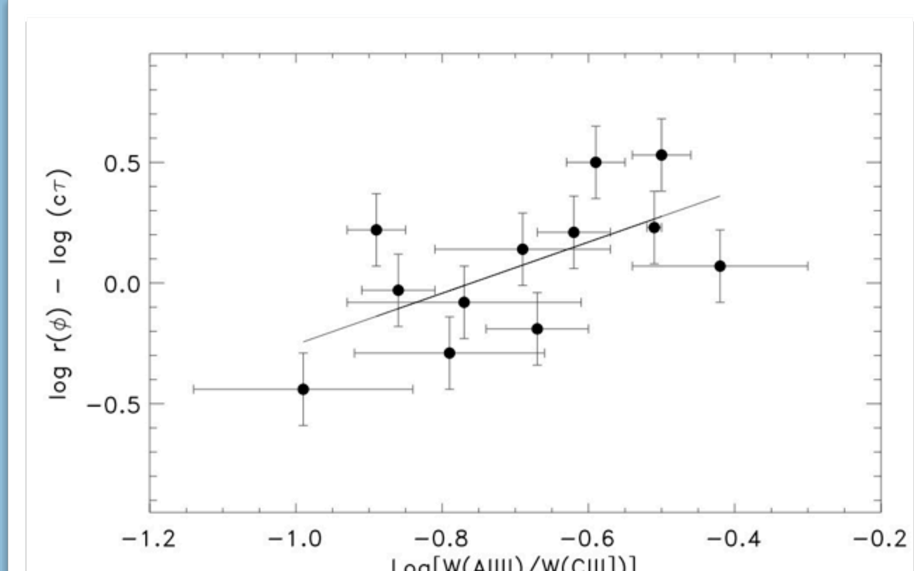
$$M_{\rm BH} = \frac{f \Delta v^2 r_{\rm BLR}}{G} = \frac{f {\rm FWHM}^2 r_{\rm BLR}}{G}$$

where f is the geometry factor and G is the gravitational constant. The **FWHM of the broad component (extracted as described in the left panel) is considered a reliable virial broadening estimator**. We show below the comparison between masses derived using the RM distance, and derived from the photoionization method.



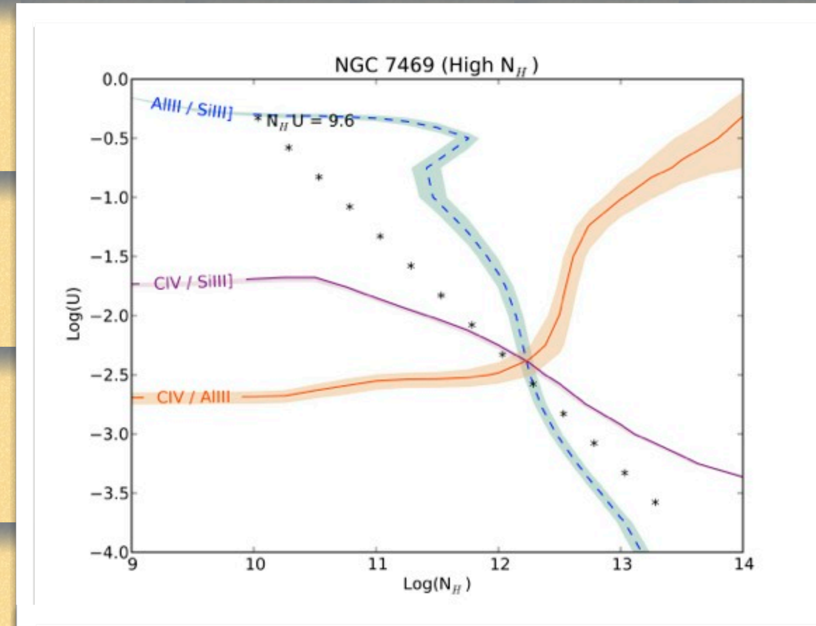
An empirical correction

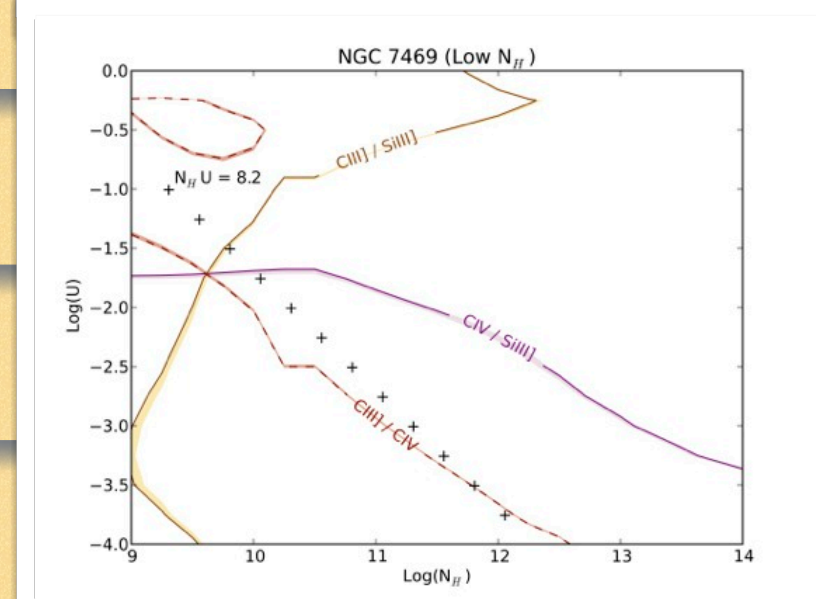
We apply a correction (figure aside) based on the CIII] λ1909 prominence:
$\log r_{BLR,\Phi} - \log c\tau \approx (1.06 \pm 0.25) \log W(\text{Al III}\lambda1860)/W(\text{C III}]\lambda1909) + (0.81 \pm 0.26)$. This correction (still uncertain) accounts for the the unresolved aspect of the BLR, and for the crudeness of the assumption of a single zone of fixed physical properties.



Diagnostics of nU

We restrict our analysis to three diagnostic ratios involving the four strongest metal lines in the spectra:
1) **Ciii]λ1909 / Siiii]λ1892** which is important because several sources show large Ciii]λ1909 equivalent widths;
2) **Aliiiλ1860/ Siiii]λ1892 that is sensitive to n_H** and believed to reflect the densest regions which are most optically thick to the ionizing continuum;
3) **Civλ1549/ Siiii]λ1892 as a marker of ionization level**.
An array of **CLOUDY simulations** (Ferland et al. 2013) at fixed **n_H** and U values allow us to study how these parameters influence the diagnostic ratios we have adopted. Our simulations assumed plane-parallel geometry, solar metallicity, column density 10^{23} cm^{-2} as well as a "standard" quasar continuum. These values allow us to draw isopleths in the n_H and U plane. The panels below show the isoplet maps based on line ratios for Siiii]λ1892, Aliiiλ1860 and Civλ1549 emission lines for one source NGC 7469. The bottom panel shows a map based on line ratios for Ciii]λ1909, Siiii]λ1892 and Civλ1549. **The crossing points give the best estimates of n** $n_H U$. We can draw two conclusions:
1) the Ciii]λ1909/ Siiii]λ1892 ratio is not representative of gas responding to the continuum changes;
2) the high density solution derived from Aliiiλ1860/ Siiii]λ1892 is representative of the reverberating gas. The Aliiiλ1860/ Siiii]λ1892 solution offers a reasonable estimate of the $n_H U$ value derived from RM.





Conclusion

We are able to estimate BLR distances from central continuum source using an independent photoionization method that yields results consistent with reverberation values and L correlation for 13 sources. Agreement with the L correlation is not surprising since we are estimating the ionizing photon flux that is related to the observed luminosity. We are able to derive empirical relations that further improve the agreement between RM and photoionization r_{BLR}. We suggest that *individually derived* r_{BLR} values can improve M_{BH} estimates, especially at z ≳ 2 when the intermediate ionization lines are shifted into the wavelength range accessible to optical spectrometers. The width of the broad intermediate ionization lines likely provides a reliable virial estimator leaving the geometry factor f and poorly understood orientation effects as the main sources of uncertainty in M_{BH} determination.

References

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