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1D AND 2D REVERBERATION MAPPING APPLIED ON THE H_β LINE OF NGC 4151

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Abstract. Using a set of observations of NGC 4151 from 1996 to 2006, we apply 1D and 2D reverberation mapping in order to find dimension of the BLR as well as its kinematical structure. We found that that the BLR size is very compact, as well as different response of the line core and wings to the continuum variation.

1. INTRODUCTION

To estimate the virial mass of Active Galactic Nuclei (AGN) from the broad emission lines one should obtain a reliable estimates of sizes of the Broad Line Region (BLR) and find a correct relation between line profiles and velocity dispersions in that gas.

Reliable BLR size measurements are now possible using reverberation mapping (RM) (the continuum/emission-line cross-correlation function). An alternative method of estimating the virial mass is based on estimating BLR distance from the central mass using photoionization theory, and the emission-line width as an indicator of the velocity dispersion.

The fundamental idea of the RM is that by observing a light echo propagating through an active galactic nuclei (AGN), one can learn about the spatial and kinematical characteristics of the BLR gas (Blandford and McKee 1982).

Because the BLR is not yet spatially resolved with interferometric techniques, RM is currently a unique spectroscopic method to have impression about the BLR size. The main properties measured by such studies are the light-travel-time (distance) between the Black Hole (BH) and BLR (determined from the time delay between

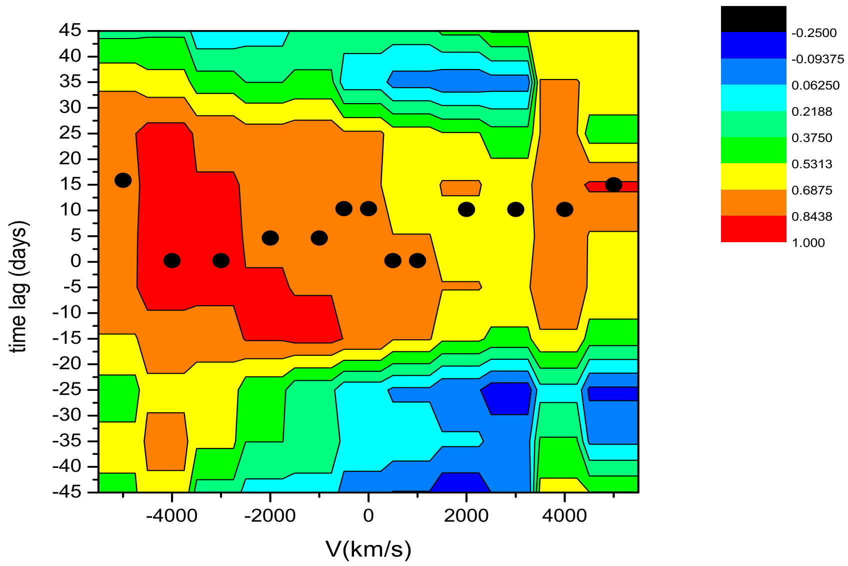

Figure 1: The 2-D CCF(τ ,V) shows the correlation of the H_β line profile with the continuum variations as a function of velocity and time delay. The points represent the centroids of the CCF.

variations in the ionizing continuum from the emission line response) and the velocity of the gas in the BLR (determined by the width of the broad emission line).

2. METHODS

The relationship between the continuum and emission lines can be written in terms of the transfer equation as:

$$L(V_z, t) = \int_{-\infty}^{\infty} \Psi(V_z, \tau) C(t - \tau) d\tau \qquad (1)$$

The functions are: C is the continuum light curve, L is the emission-line flux at line-of-sight velocity and time, and Ψ is the transfer function.

In practice most analises concentrate on solving the velocity independent transfer equation. The goal of RM is to use the observed continuum and line flux (C and L) to solve the above integral for Ψ and infer the geometry of the BLR. In the original formulation of Blandford and McKee (1982), the transfer function is obtained by Fourier methods. However the data are rarely close to regularly sampled and a very large number of data is required in order to obtain a good solution.

The cross correlation function (CCF) corresponds to transfer function convolved with autocorrelation function of the continuum. Actually, the CCF is blurred version of Ψ, the blurring depends on variability properties of the continuum (Welsh 2001). Also, Welsh (2001) emphasized that the 2D CCF(V_z, τ) has similar mathematical characteristics as a 2D response function.

Table 1: Results of 1D reverberation mapping for whole monitoring period and three subperiods based on the profile shapes (see Paper I for more details). In the first column calculated centroids of time delays are given. In the second column time delays are given. In third column CCFs corresponding to the values in the second column are given. The time lags are given in light days.

Period	H_β cent	H_β	CCF
1996-2006	69.79 ± 11.91	$5.09^{+27.89}_{-5.09}$	$0.93^{+0.01}_{-0.01}$
I	11.61 ± 2.87	$1.11^{+4.90}_{-1.11}$	$0.82^{+0.04}_{-0.05}$
II	8.15 ± 2.38	$11.15^{+5.00}_{-4.17}$	$0.88^{+0.06}_{-0.07}$
III	16.17 ± 3.14	$0.81^{+2.19}_{-0.81}$	$0.86^{+0.03}_{-0.04}$

3. RESULTS

We chose NGC 4151 as our target because it was a subject of many monitoring campaigns, as well as many authors obtain different response delays in emission lines with respect to changes in continuum (see Shapovalova et al. 2008, hereafter Paper I). So one can say that the data set of NGC 4151 is problematic thus making difficult to determine time lags. Our motivation for further investigation of this object, by means of RM, is twofold: first, results obtained from reverberation mapping provide fundamental calibration for mass estimates based on radius-luminosity scaling relationship. The second, object NGC 4151 is one of the best candidates for measuring BH mass by other means and it allows comparison between reverberation based masses and other methods.

Earlier, we performed 2D-CCF analysis of the H_α vs. continuum variation, in order to investigate the BLR structure in NGC 4151 (see Kovačević et al. 2008). In this case, we found that different lags for line wings and core correspond to the outflow model for the BLR of NGC 4151.

Now, as a next step, we analysed, in the same manner, H_β vs. continuum variation. In Paper I an inspection of the H_α and H_β profiles has been made for whole monitoring period (1996-2006) and for its different subperiods, by using spectra with a resolution of 8 Å . There we identified 3 characteristic profiles during the period 1996-2006. In the first period (I,1996-1999): where the lines were very intensive, a red asymmetry and a shoulder in the blue wing were present. In the second period (II, 2000-2001): broad lines were weaker, shoulder in the blue wing was smaller and a shoulder in red part was present. While in the third period (III,2002-2006): a blue asymmetry and a shoulder in the red part were dominant in the line profiles. As can be seen from Table 1, the second period is characterized by the largest time delay, however calculated centroid has the smallest time delay. It was shown in Paper I that CCF are small when the continuum is high.

Having this in mind, we derived from the cross-correlation functions a delay map of the H_β line segments ($\Delta v = 1000$ km/s) for the first subperiod which is shown in Fig. 1. This 2-D CCF shows some clear trends. The far red and blue H_β line wings respond with higher time lag (around 20 l.d.), while the central part and a part of blue wing has practically lag around 0. Such effects cannot be explained by a disk model or simple spherically distributed clouds for the BLR. It seems, as it was mentioned in Paper I, that there are at least two regions which contribute to the broad line profiles.

4. CONCLUSION

In this paper we used 1D and 2D RM to conclude about the size and structure of the BLR of NGC 4151. We found that the line core and line wings response different to the continuum variation, that indicates a very complex BLR in NGC4151 nucleus. We found a small time lag, that indicates a very compact BLR. Moreover, comparing this results with one obtained in Kovačević et al. (2008), both lines Hα and Hβ indicate an outflow in the BLR of NGC4151.

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