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The broad line region in Mrk 668 and NGC 4151: an outflow model

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Abstract. One of the interesting features observed in the optical spectra of active galactic nuclei (AGN) are the broad emission lines (BELs) which originate in the Broad Line Region (BLR). According to the complex lines shapes of BELs, the BLR structure is supposed to be very complex. Many different models have been proposed to explain the kinematics of the BLR, but none so far has provided a self-consistent framework for explaining the observed properties of the BEL. We propose here a new model for the BLR, which employs an accelerating outflow to explain the BEL properties in Mrk 668 and NGC 4151. We show that in both these objects, the complex BELs can be explained with this model. Moreover, the characteristics of the BLR outflow obtained from broad line fitting are in a good agreement with theoretical prediction of radio-jet formation.

Key words. galaxies: active – (galaxies:) quasars: emission lines

1. Introduction

The broad emission lines (BELs), which are the broadest emission lines in the Universe, are produced in the broad-line region (BLR) of active galactic nuclei (AGN). We know that AGN are powered by accretion onto supermassive black holes, and this energy ultimately is propagated to the broad-line emitting material, however, we still have no self-consistent model that would explain the kinematics of the BLR (Peterson 2006). The profiles of BELs are usually very complex, showing a non-Gaussian shape with some characteristic features (*e.g.*, asymmetries or bumps), that are usually variable over long time scales (see *e.g.*, Shapovalova et al. 2004). This leads to a conclusion that the BLR is a complex region, possibly composed of more than one kinematically different components. A number of models have been proposed to explain the kinematics and geometry of the BLR, including a biconical ejection (Zheng et al. 1990), disk wind (Murrey & Chiang 1995), a two-

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component model that contains a disk-like and spherical component (cf. Popović et al. 2004). However, none of these models explains the entire range of the BLR properties. Moreover, in some AGN (*e.g.* Mrk 668, 3C390.3), a single model has failed to explain line profiles from different epochs. There are indications that some of the BLR properties may be related to outflows and jets originated from a close vicinity of the black hole and accretion disk (*e.g.,* Arshakian et al. 2006). Recent studies of the radio-jet formation indicate that jets undergo a substantial acceleration near the black hole (Marscher, A. P. 2005; Lobanov A. 2007). The aim of our work is to investigate whether accelerated outflows may have an effect on the broad-line emission. Therefore, we introduce the possibility of acceleration of the outflowing material in the BLR. We study here two well known AGN, NGC 4151 and Mrk 668, that are part of a larger work where we analyze the optical spectral and VLBI monitoring data for the better understanding of processes occurring in AGN. We choose these objects to test our model because they exhibit very complex and peculiar BEL profiles. Mrk 668 is a broad-line radio galaxy with peculiar BEL profiles (Marziani et al. 1993; Gezari et al. 2007), while NGC 4151 is the brightest Seyfert 1.5 galaxy exhibiting highly variable BEL profiles (Shapovalova et al. 2008).

2. An outflow model for the BLR

In our model, we assume an accelerating outflow in an emitting region extending from an inner radius R_i to an outer radius R_o. We postulate that the outflow starts within a few tens of the gravitational radii, R_g, from the central black hole and that its velocity $V(r)$ can be described as a function of the distance, r, from the black hole

$$V(r) = V_0\left(\frac{R_i}{r}\right)^{p_1}$$

where V_0 is the initial velocity at R_i and p_1 is a power-law index which is negative in the case of the accelerating outflow. Assuming that the acceleration stops at a radius R_a from the black hole, we can expect that for $r > R_\mathrm{a}$ the velocity of the outflow is decreasing exponentially, with a different power-law index p_2 as

$$V(r) = V(R_\mathrm{a})\left(\frac{R_\mathrm{a}}{r}\right)^{p_2}$$

where $V(R_\mathrm{a})$ is the radial velocity at R_a, which can be calculated from

$$V(R_\mathrm{a}) = V_0\left(\frac{R_\mathrm{i}}{R_\mathrm{a}}\right)^{p_1}$$

As we have some distribution of emitters across the outflow, we assume that the brightness of the outflowing material is strong and flat up to a radius R_e, i.e.

$$\varepsilon(r \leq R_\mathrm{e}) = \varepsilon_0,$$

after which it decreases exponentially

$$\varepsilon(r > R_\mathrm{e}) = \varepsilon_0\left(\frac{R_\mathrm{e}}{r}\right)^{p_3}$$

Additionally, we introduce a random velocity component, assuming that it is changing across the emission region, i.e. increasing while the outflowing material is accelerating and decreasing afterwards. Thus, the maximum of the random velocity occurs at the radius R_e. Thus, we have for the random velocity V_ran:

$$V_\mathrm{ran} = \begin{cases} V_\mathrm{ran}^\mathrm{max}\sqrt{\frac{r}{R_\mathrm{e}}}, & r < R_\mathrm{e} \\ V_\mathrm{ran}^\mathrm{max}\sqrt{\frac{R_\mathrm{e}}{r}}, & r > R_\mathrm{e} \end{cases}$$

where $V_\mathrm{ran}^\mathrm{max}$ is the maximal random velocity. Since the outflow starts very close to the black hole, we take into account the gravitational redshift, i.e. the shift of a line can be calculated as $\frac{\Delta\lambda_g(r)}{\lambda} = -1 + \sqrt{1 - \frac{2}{r}}$, where r is in gravitational radii.

At the end, we calculate the total line profile assuming that contributions from each individual component of the BLR to the broad line profile can be represented by the Gaussian function. The resulting line profile is then given by

$$I(\lambda) = \frac{1}{R_\mathrm{o} - R_\mathrm{i}}\int_{R_\mathrm{i}}^{R_\mathrm{o}} \varepsilon(r)\cdot e^{-F(r)}dr$$

where $F(r)$ is defined as

$$F(r) = \left(\frac{\lambda - \lambda_0 - \Delta\lambda_r(r) - \Delta\lambda_g(r)}{W(r)} \right)^2$$

Here $\Delta\lambda_r(r)$ determines the radial velocity in the following way

$$\Delta\lambda_r(r) = \frac{V(r)}{c}\lambda_0$$

and $W(r)$ gives the random velocity as

$$W(r) = \frac{V_{\rm ran}(r)}{c}\lambda_0$$

3. Application to the observed BEL

We apply the proposed model to the observed Balmer line Hα of active galaxies NGC 4151 and Mrk 668. The data for NGC 4151 were obtained by Shapovalova et al. (2008), while Mrk 668 data were provided by M. Eracleous. In Fig. 1 the Hα line is fitted with the model and Fig. 2 gives the velocity fields for both galaxies. From Fig. 1, it is evident that the model can describe well the observed emission line profiles. The predicted outflow acceleration, up to distances of $\approx$ 500 $R_{\rm g}$ (Fig. 2), is in a good agreement with theoretical models of jet formation in which the initial acceleration of the flow occurs in the same range of of distances from the central black hole (*e.g.*, Marscher 2005, Lobanov 2007). Fig. 3 gives a basic sketch of an AGN featuring a relativistic jet and its environment (Lobanov 2007) where we can see that the span over which the jet acceleration occurs coincides well with the acceleration of the outflowing material in the BLR.

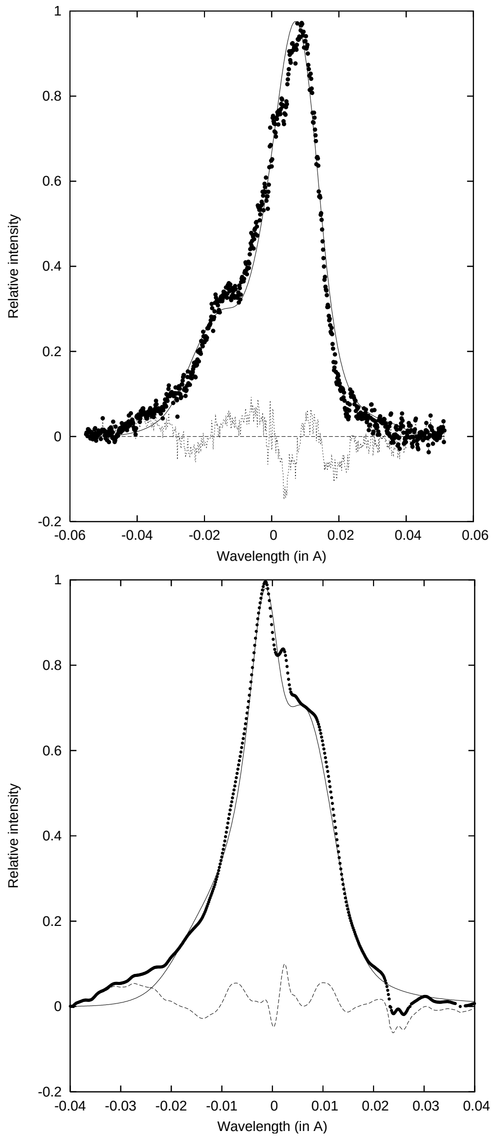

Fig. 1. Modeled line profile (solid line) in comparison with the observed Hα line (dots) for the case of Mrk 668 from the epoch February-1990 (*upper panel*) and for NGC 4151 (*bottom panel*). The Hα of NGC 4151 is averaged over the period 2002 - 2006.

4. Conclusions

We have proposed here a model to explain the peculiar and complex line shapes of BELs. The model assumes that the broad lines originate in an accelerating outflow affected by the gravitational field of the black hole. We have applied the proposed model to the Hα line of NGC 4151 and Mrk 668 and showed that the model could explain the complex line profiles for some epochs (Fig. 1 & 2). The acceleration scales of the outflow agree well with the expectations coming from modeling the relativistic flows in AGN (Marscher 2005, Lobanov 2007). This suggests that an accelerating outflow provides a viable explanation for the BLR

Table 1. Model fitting results. R_i is the inner radius of the emitting region, R_o is the outer radius, R_a is the radius where acceleration stops, R_e is the radius after which emission is decreasing, W_0 is the starting random velocity, V_0 is the starting velocity of the outflow, p_1, p_2, p_3 are the power law indexes of the velocity distributions of accelerating outflow, de-accelerating outflow and emissivity distribution, respectively.

Object	R_i [R_g]	R_o [R_g]	R_a [R_g]	R_e [R_g]	W_0/λ	V_0 [km/s]	p_1	p_2	p_3
Mrk 668	25	615	500	190	0.0083	0.0125	-4.5	3.3	0.5
NGC 4151	20	2200	500	260	0.0083	0.0125	-4.1	2.0	0.5

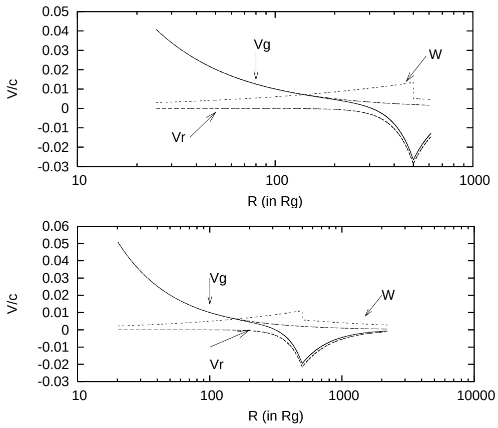

Fig. 2. Velocity field for the case of Mrk 668 (*upper panel*) and NGC 4151 (*bottom panel*). All three velocity distributions are marked on the plots. The total velocity is given with the filled curve.

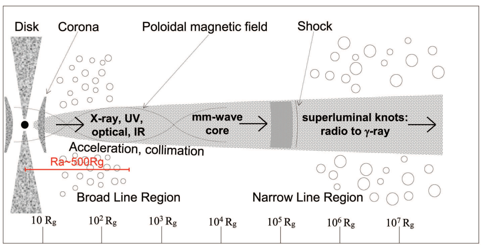

Fig. 3. Basic sketch of an AGN featuring a relativistic jet and its environment. Reproduced from Lobanov (2007). The radius of the acceleration outflow in the BLR is showed with the red line.

geometry. We plan to test this model further using all data from our monitoring project in order to explain the variability of the BEL profiles in these two galaxies (Popović et al. 2008b).

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