Kinematics and physics of emitting plasma around super-massive black holes

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Abstract. A group of galaxies emits strong permitted and forbidden lines from the central part where a massive black hole is supposed to be located. The cores of this type of galaxies, so called Active Galactic Nuclei (AGN) are known as a most powerful sources of radiation in the Universe. Here we discuss the emitting plasma conditions in emitting line regions of AGN as well as methods which are in usage to determine the physical properties of the emitting plasma around super massive black holes.

1. Introduction
Investigation of the nature of emitting ionized gas in galactic nuclei of Seyfert galaxies, radio galaxies, QSOs, blazars (collectively called Active Galactic Nuclei - AGN) is one of the important subject in astrophysics today [1, 2]. First, by investigating of the processes in central part of these objects we can learn about the innermost part of other 'normal' galaxies. Second, AGN are the most powerful sources, located at different cosmological time-scales, consequently their investigations are cosmologically important. Finally, the 'central engine' inputs enough energy in surrounding gas, creating emitting plasma that is located very close to a massive black hole and this presents an unique case that allows us to study relativistic effects in the emitting plasma.

The massive black hole which is fed by matter subjects their environs to extremes of ionization or temperature. There is present gas which is irradiated by X-rays. Also massive outflows of material or highly relativistic jets can be present where ionization is caused by shocks. Therefore, in AGN the physical conditions are typical for 'classical' plasma and all processes which are characteristic for 'classical' plasma can be significant; i.e., the photoionization, recombination and collisions can be considered as relevant processes in this type plasma.

The narrow and broad emission lines are present in spectra of AGN. Their shapes and intensities give us opportunity to investigate the physical and kinematic properties in the central part of AGN. Narrow emission lines originated in an extensive region (so called Narrow Line Region - NLR) which can be resolved in the nearest AGN, while Broad Emission Lines (BELs)
are formed in a very compact region (so called the Broad Line Region - BLR) in the central part of AGN. The investigation of BEL shapes provides information on conditions of the emitting gas surrounding a black hole, supposed to be in the center of these objects.

Here we give a short overview of our investigations of the kinematics and physics of emitting plasma around super-massive black holes.

2. AGN: model

According to the standard model of AGN [2], an AGN consists of a black hole \((10^6 \text{ – } 10^9 \text{ Solar masses})\) surrounded by a (X-ray and optical) continuum emitting region probably with an accretion disk geometry. The BLR region is located farther away from the X-ray emitting region, and it is in size around several light days. The most extensive region is the NLR. As an example of emitting region in AGN, in figure 1, we show a map of this region of Mrk 817, a Sy 1.5 galaxy [4], where an outflow in the NLR is present.

2.1. Accretion disk: The X-ray emitting region

Variability studies of AGN indicate that the size of the X-ray emission region is of the order \(10^{14} \text{ – } 10^{15} \text{ cm}\). An Fe K\(\alpha\) fluorescence line detected in several AGN near 6.4 keV is thought to originate from within a few \(10^2\)s of gravitational radii (see figures 2 and 3). This line is thought to be a fluorescence line of Fe due to emission from a cold or ionized accretion disk that is illuminated from a source of hard X-rays originating near the central object [3, 5]. Aspects of this emission can provide a probe of strong gravity near a black hole as well as physical conditions of plasma in a strong gravitational field. The AGN Fe K\(\alpha\) line shapes indicate presence of an accretion disk, that is an indication of black hole presence in the center of these objects. An example of the influence of the gravitation of massive black hole on Fe K\(\alpha\) line shapes is illustrated in figures 2 and 3. As one can see in the figures the shapes of the Fe K\(\alpha\) line are different for different metrics. Moreover, the long red wing and strong blue peak indicate that the emission is created very close to the black hole.

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Figure 1. The model of the emitting region of the AGN of Mrk 817 galaxy. The BLR is assumed to be composed of an accretion disk and a spherical region. The NLR is also composed of two regions, where in one of them (closer to the black hole) an outflow is present (see [4]).
2.2. The BLR and NLR: The UV and optical emitting region

The detailed map of NLRs showed that the NLR is extended on scales of several parsecs (to several 100 pc) [6], in contrast to the BLR which is point-like on direct images consistent with the observed temporal variability on short time scales [7]. This result provided an observational proof to the findings of the theoretical analysis of the line widths and ratios in earlier optical spectra of Seyfert 1s, that the broad and the narrow lines originated from two separate regions differing by their dimension and the physical conditions of the plasma. The estimated electron number density in NLRs is from $10^3$ to $10^7$ cm$^{-3}$, while the electron number density is higher in BLRs (about $10^9 − 10^{12}$ cm$^{-3}$) [1, 2]. Also, the velocities of emission gas in these regions are different; the velocities in the NLR are of the order of several 100 km s$^{-1}$, while in BLR are several 1000 km s$^{-1}$. The dimension of the BLR is significantly smaller than the NLR (from several light days to several 100s light days [7]).

Concerning NLRs, NLR emission line ratios are remarkably uniform, displaying only very small variation between Seyfert galaxies, and even less within an individual object. Dusty,

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Figure 2. The accretion disk (top) and the shape of the Fe Kα line (bottom) in Schwarzschild metric

Figure 3. The same as in the figure 2, but for the Kerr metric.
radiation pressure dominated photoionization models with a simple physical mechanism can reproduce this spectral uniformity between different AGN [1, 2]. Using the forbidden narrow [OIII] and [NII] line ratios, one can diagnose the emission gas parameters in these regions (electron density and temperature). On the other hand, the line shapes and ratios in BLRs are more complex (see e.g. the Hβ in figure 4). Although photoionization calculations have reached a high level of sophistication, providing relatively good constrains on the density and temperature [8], these calculations do not reveal the origin and geometry of the emission gas. Here, we will present some of our investigation concerning the physics and geometry of the BLR using the broad emission spectral lines. Also, we note here that, due to low-density plasma and high random velocities in the BLR, only Doppler effect can be considered as relevant broadening mechanism in emission line regions of AGN.

Figure 4. The complex Hβ line of Mrk 817, fitted with several Gaussian components presented bottom (with the solid line the broad components and with dashed line the narrow components are presented). The broad feature denoted with the dashed line represents the Fe II template.

Figure 5. The broad Hβ line of Mrk 817 fitted with the two-component model, after subtraction of the narrow and satellite lines. Relative intensity vs. x is presented, where $x = (\lambda - \lambda_0)/\lambda_0$.

3. The BLR plasma: kinematics and physics
As it was mentioned above, the forbidden lines emitted from NLRs can be used to diagnose the plasmas parameters in this region (electron density and temperature), while taking into account complexity of the BLR it is hard to have an exact method to find these parameters. First, as it can be seen in figure 4, the broad lines are complex, and besides it, there is a number of satellite lines which should be subtracted from the spectra. In figure 4 we presented the Gaussian decomposition of the Hβ of Mrk 817, the solid Gaussians bottom presents the decomposition of the broad Hβ line, while the dashed lines are decompositions of the narrow [OIII] and Hβ lines. Also, a complex template of the Fe II lines is present in the Hβ wavelength range (denoted as dashed broad feature in figure 4). After subtraction of these lines (figure 5) one can use the broad lines in order to investigate the physics of the BLR.

3.1. The BLR kinematics
The concept of disk geometry in the BLR is very attractive because of the most widely accepted model for AGN which includes a super-massive black hole fed by an accretion disk. The detection and modeling of double-peaked emission lines [9] gives proof to the presence of accretion disks,
even though the number of AGN with double-peaked or broad emission lines is still statistically insignificant (about 5%). Beside of the disk geometry, in the BLR can be present outflows and inflows (so called jet geometry), and spherical geometry (with isotropic velocities). More detailed discussion about the BLR geometry is given in [10]. Recent investigation given in [11– 16] showed that the BLR of some AGN could be complex and composed of two components: (i) an accretion disk and (ii) a region with geometry different from the disk. The model can well describe the complex line shapes (see figure 5). It may indicate that broad lines are created in an accretion disk and that an additional emission (contributing mainly to the line core) coming from a region that may be created by winds from the accretion disk.

3.2. Balmer line intensities and the BLR physics
The broad line strength, width and shape are powerful tools for gas diagnostics in the different parts of the emitting region of AGN [1, 2]. Different types of physical conditions and processes

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**Figure 6.** The Boltzmann-plots of the Balmer series originated in the BLR of several AGN (see [19] for more details).

**Figure 7.** The determined temperature as a function of Full Width at Half Maximum (top) and Full Width at Zero Intensity (bottom).
can be assumed in order to use the emission lines for diagnostics in the emitting plasma [8], especially the broad lines from Balmer series, which are usually very strong in spectra of an AGN. However, there is the problem that the broad emission lines are complex and that they are probably coming from at least two regions with different kinematic and physical conditions [11–16]. Furthermore, the broad emission line profiles of some AGN may be explained with a two-component model. As a starting point, it is possible to assume that: (i) the BLR is at least partly optically thin [17], (ii) the broad emission lines from a series (like the Balmer one) are coming from the same region (or from a region having similar physical properties).

Taking into account these assumptions, we apply well known method for diagnostic of laboratory plasma, the Boltzmann plot (BP) method [18] to the Balmer line series. It is interesting that in a fraction of AGN the BP method can be applied to the Balmer series (see figure 6) and it indicates presence of Partial Thermodynamical Equilibrium (PLTE, see [19]) in the BLR of these AGN. Our investigation on a sample of 90 AGN with broad emission lines (Sy 1 and quasars) shows that in about 30% of these galaxies the BP method can be applied to obtain some estimates of the BLR temperature [19, 20]. The obtained temperature are within the range from 5000 K to 15000 K, that is in agreement with previous estimations for the BLR. Moreover, we found that a correlation between the temperature and broad line widths is present (figure 7).

4. Conclusion
In this work we give a short overview of our work on the kinematics and physics of emitting plasma that is located very close to massive black holes. Around a massive black hole one can expect very dynamical processes resulting in accretion of matter to the black hole. This can be seen from the shape of the Fe Kα line (high blue peak and a strong red wing). Also, the signature of an accretion disk can be present in the optical broad emission lines (i.e. lines from the Balmer series, see figure 5). Applying the BP method to the Balmer line series we found that it is likely that broad optical lines are coming from plasma where (at least in a part of the BLR) PLTE may be present. The obtained temperatures from BPs are \( \sim 10^4 \) K that is in an agreement with previous investigation.

At the end let us point out that even such extensive and complex region around massive black holes as the BLR is can be investigated by methods which have been applied in laboratory plasmas, as the BP method.

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