Broad emission lines: A tool for studying nuclei of active galaxies

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Abstract. Active galactic nuclei (AGNs) are objects hosting in their center a super-massive black hole (SMBH) with an accretion disk surrounded by gas and dust. The mass of an SMBH can be derived from the dynamics of the gas gravitationally bounded to the SMBH. This is the case for the broad line region (BLR), i.e. a photoionized gas in the vicinity of an SMBH that emits broad emission lines (BELs), which properties can be used to estimate the mass of the SMBH. In spite of a number of papers devoted to the BLR research, its true nature is not well known. Therefore, it is still important to investigate the BLR structure (size, geometry, physics, etc.), where one of the aims is to better constrain the mass of the SMBH in the center of AGNs. The BELs are the only signatures of the BLR physics and geometry. They can be clearly identified in AGN spectra and they often show complex profiles. Their fluxes, profiles and ratios can provide much information about the BLR geometry and physics. Moreover, the BELs and continuum flux are very often varying in AGNs. Therefore, an investigation of the BEL flux and profile variability during a long period is another useful tool for mapping the geometrical and dynamical structure of the BLR. In this review we present and discuss some tools and techniques for studying the structure of the BLR using broad emission line properties.

1. Introduction

One of the important problem of active galactic nucleus (AGN) investigations is the most accurate estimation of the mass of the super-massive black hole (SMBH) in the center of an AGN. A direct determination of an SMBH mass is possible from dynamical methods (virial theorem) based on observations of the kinematics of stars orbiting around the SMBH. In the case of an AGN, the SMBH mass can be derived from the dynamics of the gas gravitationally bounded to the SMBH. The intensive broad emission lines (BELs), visible in the spectrum of Seyfert 1 galaxies and quasars (commonly called type 1 AGN), originate relatively close to the central power source, i.e. in the broad line region (BLR). The BLR is in the strong
interaction with the radiation field produced by the central engine and is under the influence of the gravitational field of the SMBH, thus can be used to determine the SMBH mass using the virial theorem (see e.g. Gaskell 1988). Therefore, investigations of the BLR structure (size, geometry, physics, etc.) are very important, and for this the analysis of the BELs properties (flux, profiles, widths, etc.) is needed.

A lot of work has been devoted to understand the relationship between the BLR dynamics and the corresponding broad emission line profiles (see e.g. Sulentic et al. 2000, Gaskell 2009, and reference therein). The BLR is probably very complex, often with evidence for multiple components (Popović et al. 2004, Ilić et al. 2006, Bon et al. 2006, 2009), thus the BELs are the result of a combination of effects involving the gas motion and the radiation transfer across an environment which is only approximately understood. Moreover, in some AGNs (especially with a high variability in the line profiles) there may be an additional component (e.g. outflowing material or disk wind) present in the BLR that strongly affects the BEL profiles (as e.g. in NGC 4151, see Shapovalova et al. 2008, 2010a). As an example see Fig. 1, where the typical multi-Gaussian line fitting (see e.g. Popović et al. 2004, Sulentic et al. 2000, and references therein) is given for the case of the H\(\beta\) emission line of Mrk 817 (Ilić et al. 2006). The broad H\(\beta\) is fitted with three Gaussians (solid lines at the bottom of Fig. 1) indicating that there may be a disk-like emission component that contributes to the line wings, and an additional component contributing to the line core (Ilić et al. 2006).

![Figure 1. An example of the multi-Gaussian fitting of the H\(\beta\) emission line of Mrk 817 (Ilić et al. 2006). The dots represent the observation and solid line is the best fit. The Gaussian components are shown at the bottom. The dashed lines represent the Fe II template, [OIII] and H\(\beta\) narrow lines.](image)

On the other hand, the physical properties (e.g. gas temperature, density, ionization parameter) of the emitting plasma in the BLR are still not well constrained. The BELs always come from the permitted line transitions (or sometimes semi-forbidden) which is obviously implying that the densities are high enough to collisionally suppress the forbidden emission lines. Thus, the standard nebular diagnostics developed for HII regions or planetary nebulae cannot be applied (Osterbrock & Ferland 2006). There are several numerical codes (as e.g. CLOUDY, Ferland et al. 1998), which use the photoionization model to explain the observed line ratios in AGNs and obtain the physical parameters of the BLR (see e.g. Korista & Goad 2004, Marziani et al. 2010). Moreover, the BEL fluxes could be used to probe the physical conditions of the BLR plasma using well-known laboratory plasma diagnostic tools, as e.g. the Boltzmann-plot (Griem 1997) that has been applied to the Balmer line series (see e.g. Popović 2003, 2006ab, Popović et al. 2008, Ilić et al. 2009, 2010a, 2012). It is believed that the photoionization is probably the main heating mechanism, but the line production can be influenced by other atomic processes, especially those caused by high density effects. For example, in the case of NGC 4151, a well-studied Seyfert 1.5 galaxy (see e.g. Peterson et al. 2004, Bentz et al. 2006, Metzroth
et al. 2006, Shapovalova et al. 2008, etc.), during one observed period, the line fluxes are not correlating with the continuum flux and are saturating at higher continuum fluxes, indicating a presence of a non-radiatively heated region in the BLR, or more ionizing to optical flux ratio than expected for a typical AGN (Shapovalova et al. 2008).

Moreover, the BELs of AGNs often exhibit variability, which is assumed to be caused by variation in the ionizing continuum strength and by dynamic evolution of the BLR gas on long timescales. A long-term optical spectral monitoring of the nucleus of some AGNs has revealed a time lag in the response of the broad emission lines relative to flux changes in the continuum (see e.g. Wanders and Peterson 1996, Kollatschny & Dietrich 1997, Peterson 2008), that is used as a tool for determination of the size of the BLR. Nowadays this method is called the reverberation mapping technique (Blandford & McKee 1982), and has motivated and initiated numerous monitoring campaigns (see e.g. the international “AGN Watch” campaign, Peterson 1999).

In this paper we will present some methods to study the physics and kinematics of the BLR using the emission lines and their properties (fluxes, profiles, variability), especially we will present some results based on our long-term optical spectral monitoring campaign of a sample of type 1 AGN (Shapovalova et al. 2004, 2009, 2010b, 2012).

2. Line fluxes: Plasma diagnostics of the BLR

The physical properties of the BLR are difficult to estimate directly from the BELs, that are basically the only signature of the BLR. The plasma conditions in the BLR are more closer to the conditions in stellar atmospheres than in gaseous nebulae (Osterbrock & Ferland 2006), that we deduce from the presence or absence of some emission lines. The temperatures ought to be less than 35 000 K since at higher temperatures the observed Fe II (that is sometimes even remarkably strong) would be effectively suppressed by the collisional ionization to Fe III.

On the other hand, the electron density should be in the range $10^8 < n_e < 10^{14} \text{cm}^{-3}$, in order to suppress the emission of broad forbidden lines, while still allowing for the presence of permitted and semi-forbidden ones.

There are couple of methods how to determine the BLR physical properties using only observations of the BELs (Laor 2006, Marziani et al. 2001, Popović 2003, 2006). Marziani et al. (2001) found, using the CLOUDY photoionization computation, that the ratio between UV emission lines Si III $\lambda 1892$ and C III $\lambda 1909$ is a good density diagnostic in the density range $9.5 < \log n_e < 12$. Also, Laor (2006) considered electron scattering influence on the line shapes and determined the physical parameters (the electron density and optical depth) of the BLR by fitting the emission lines that have exponential wings, in the case of the low luminosity AGN NGC 4395. However, the problem of these direct methods for BLR diagnostics is that they are observationally constrained for either needing the UV observations or detecting BELs with strong exponential line wings.

Popović (2003, 2006) suggested that the Boltzmann-plot (BP) method, already well known to laboratory diagnostics of a high density plasma (Griem 1997), might be exploited to probe the BLR of some AGNs (see also Ilić et al. 2006, La Mura et al. 2007, Popović et al. 2008). The BP method uses the fluxes from one line transition series (as e.g. hydrogen Balmer line series) and the atomic parameters of the corresponding line series, to estimate the excitation temperature of the BLR plasma from the slope $A$ of the line fluxes (normalized to the corresponding line atomic parameters) versus the energy of the upper level (Griem 1997, Popović 2003, 2006): $A = \log_{10}(e)/kT_{exc} \approx 5040/T_{exc}$. For example, in case of NGC 5548 the BLR temperature was estimated using the BP applied to the Balmer lines observed from 1996 to 2004 (Popović et al. 2008), and a high correlation between the variation of the optical AGN continuum and the BP temperature is found. The advantage of the BP method compared to the other BLR plasma diagnostics methods that use BELs, is that it requires only the measured Balmer line fluxes.
to estimate the excitation temperature. But one has to consider some possible drawbacks, concerning the use of complex BELs to infer the BLR physical properties, which in general appear in all methods (see Ilić et al. 2006 for discussion).

Recently, Ilić et al. (2012) investigated for what physical conditions the BP can be applied to the BLR plasma diagnostics, using the hydrogen Balmer line series obtained in three different ways: with the CLOUDY spectral synthesis code (Ferland et al. 1998), from the recombination theory (Storey & Hummer 1995), and from the Sloan Digital Sky Survey (SDSS) database (La Mura et al. 2007). It was shown that the plasma temperatures can be estimated using the BP, applied on the hydrogen Balmer line series, in the case of a high density BLR, i.e. the electron density is $n_e \sim 10^{14} \text{cm}^{-3}$ (Ilić et al. 2012). Moreover, for these cases the electron temperature can be estimated from the BP excitation temperature. Fig. 2 presents the BP temperature as a function of the electron temperature, for cases when the BP fitting error is less than 10%. Clearly, there is a relation between these two temperatures, especially for the electron density of $10^{14} \text{cm}^{-3}$ (open circles in Fig. 2).

$$T_{BP} = 30000 \text{ K}$$ (Ilić et al. 2012).

### 3. Line profiles: BLR geometry

The analysis of the BEL profiles (widths, shapes, asymmetries, and bumps) is a powerful tool to study the kinematics and geometry of the BLR (see e.g. Sulentic et al. 2000, Popović et al. 2004, Gaskell 2009). As noticed in the Introduction, the BEL profiles are usually very complex, showing a non-Gaussian shape with some characteristic features (e.g. asymmetries or bumps), implying that the BLR is most likely a complex region, that cannot be explained in terms of a simple single-region model. So far there are numerous geometrical models proposed to explain the kinematics and geometry of the BLR (e.g. biconical ejection, disk wind, combination of the disk-like and spherical component etc.), and we still have no self-consistent model that would explain the kinematics of the BLR in all AGNs (Peterson 2006). For example, there are indications that the BLR kinematics may be related to outflows and jets originating from a close vicinity of the supermassive black hole and accretion disk (e.g. Arshakian et al. 2010). Thus, one of the proposed models assumes that the BELs originate in an accelerating outflow affected by the gravitational field of the SMBH, and this model has been tested for several AGNs, as NGC 4151 or Mrk 668 (see Ilić et al. 2008, 2010b).

On the other hand, the Keplerian accretion disk model of the BLR has been often proposed to explain the BEL double-peaked profiles (see e.g. Chen et al. 1989, Chen & Halpern 1989,
Eracleous & Halpern 1994, 2003, Popović 2006b, Popović et al. 2002, 2004, Kollatschny & Bischoff 2002, Bon et al. 2006, 2009 etc.). The fraction of AGNs that clearly shows double-peaked profiles, and thus the evidence of the disk-like geometry, is small and statistically insignificant (e.g. Strateva et al. 2003). But, the presence of double-peaked lines is not required as a necessary condition for the existence of a disk-like geometry in the BLR. In the case of single-peaked lines, it could be that either the parameters of the disk (e.g. the inclination) are such that one observes single-peaked lines (e.g. Popović et al. 2004, Ilić et al. 2006) or the emission of the disk is masked by the emission of another emission line region (see e.g. Popović et al. 2002, 2004, Bon et al. 2006, 2009, Ilić et al. 2006, and references therein). The last proposed case is the so-called two-component model (see Popović 2006b, for a review). One possibility of the two-component model is to have a disk region where the line-wings are originating, and an additional spherical component, which is producing the line core and whose kinematics can be described with an isotropic velocity distribution (Popović et al. 2004, Bon et al. 2009). Another important model is a disk-like region with the disk wind that can also produce single-peaked BELs observed in most of AGNs (see e.g. Murray & Chang 1997, Flohic et al. 2012, and references therein).

Finally, one should consider BEL profile fittings with cautions as the same line profile can be modeled with more than one model. For an example, in Fig. 3 we present the BEL profiles of AGN Mrk 817 fitted with two different models (Ilić et al. 2006). The BLR of Mrk 817 might be composed from either disc-like+spherical regions (left panel, Fig. 3) or from two spherical regions, having different velocity distributions (right panel, Fig. 3).

![Figure 3](image_url). The averaged broad profile of the Hα and Hβ emission lines of Mrk 817 fitted with the two-component model: disk plus additional component (left). The broad profile of the Hβ emission line fitted with only two Gaussian components (right). For details about the models see Ilić et al (2006).

4. Line variability: Long-term optical monitoring campaign
The long-term optical monitoring campaign consisted from coordinated international observations of a sample of type 1 AGN, constantly carried out at four telescopes of Russia and Mexico during the period 1996–2012. The main aim of the campaign is to monitor the variability of BELs in the optical domain (spectral ranges near Hα and Hβ) and continuum, and investigate the structure (physics and kinematics) of the BLR in type 1 AGN.

The used instruments are: the 6-m and 1-m telescopes of SAO RAS, the 2.1-m telescope of INAOE (Cananea, México), and the 2.1 m telescope of OAN-SPM (Baja California, México).
High quality spectra (S/N > 50) around Hα and Hβ wavelength region (spectral range 4000-8000 Å, the resolution 3-15 Å) were obtained with long-slit spectrographs equipped with a CCD. For details on data acquisitions, data reduction and calibration see Sahpovalova et al. (2008, 2010b). The sample of observed AGNs contains well-known and studied objects: NGC 5548, NGC 4151, 3C390.3, Ark 564, and Arp 102B. So far, the results of this campaign have been presented and published in a number of papers (for more details see e.g. Shapovalova et al. 2001, 2004, 2009, 2010ab, 2011, 2012, Popović et al. 2008, 2011, Ilić 2007, Jovanović et al. 2010). Here we present in more details results obtained for 3C390.3 and Ark 564.

4.1. The case of 3C390.3

One of the monitored AGN is a radio-galaxy 3C390.3 showing double-peaked broad emission lines. The observations of 3C 390.3 were performed from 1995 to 2007. The results of these investigations were published in Shapovalova et al. (2001, 2010b), Popović et al. 2011 and Jovanović et al. (2010). The double-peaked Hα and Hβ lines clearly indicate a disk-like geometry of the BLR. But, the variations in line profiles show that there is an additional emission component contributing to the line core, that is originating in the region different then the disk (see the mean and rms Hα spectra in Fig. 4, and for more details see Fig. 12 in Shapovalova et al. 2010b). This additional component could be also explained as an extra emission coming from the perturbation in an accretion disk (Jovanović et al. 2010).

![Figure 4. Mean and rms spectra of the Hα line of 3C390.3 from the whole monitoring period (1995–2007) (Shapovalova et al. 2010b).](image)

Fig. 5 gives the light curves of the continuum flux (top) and the flux of the broad component of the Hβ line (bottom). Both light curves have similar behavior, but the cross-correlation analysis gives that the Hβ flux is delayed for ~95 days (Shapovalova et al. 2010b). We can basically divide the monitoring period into two: period I - until 2002, and period II - after 2002, when there is a clear outburst seen in both light curves (red vertical line in Fig. 5).

One of the interesting results comes from the analysis of the line emission profiles from different epochs, i.e. the line fluxes of different line segments. Line profiles were divided along the velocity scale into nine line segments (see Table 2 in Popović et al. 2011), where e.g. line segments -4 and -3 represent together the blue wing flux and line segments 4 and 3 the red wing. We focus on the analysis of the line wings, since for them the emission of the accretion disk is contributing the most (Fig. 6). Using the disk model for the line profiles, we have shown that the change in the line profile wings in the period I (full circles), can be explained if the location of the disk emitting the broad lines is shifted along the accretion disk (blue line with
4.2. The case of Ark 564

In the following section, we will present in more details the latest research and results obtained for the narrow-line Seyfert 1 galaxy Ark 564. The observations of this AGN were performed from 1999 to 2010 (for details see Shapovalova et al. 2012). One of the reasons why narrow-line Seyfert 1 (NLS1) galaxies are interesting is the prominent emission of Fe II in the optical band around the Hβ line (Fig. 7), that is clearly visible due to the relatively small width of the emission lines in this type of AGNs. From the multi-Gaussian fitting of the wavelength range of 4000–5600 Å, and the analysis of the Gaussian line widths and shifts, we have shown that the...
optical Fe II lines of this AGN are coming from the intermediate line region (Shapovalova et al. 2012), as suggested before (see Kovačević et al. 2010, and references therein).

During the monitoring period, the mean continuum and lines fluxes are weakly varying, as the decrease of only ∼20%-30% (see light curves in Fig. 5 in Shapovalova et al. 2012) from the beginning (1999) to the end of the monitoring campaign (2010) was detected. Also, in the light curves, five flare-like events (two prominent and three possible) lasting ∼1-3 days were detected.

One obtained result is particularly intriguing. It was observed, that there is almost no correlation between the Hα and Hβ line fluxes (Fig. 8). Such behavior is unexpected if photoionization by the central continuum source would be the main mechanism responsible for the production of both lines. The lack of correlation could indicate very complex physical processes in the line forming region, i.e. beside the photoionization some additional physical processes may be present.

5. Conclusions
In this paper we present some methods and tools how to investigate the plasma properties of the BLR in AGNs, using the broad emission line parameters (e.g. line fluxes, ratios, widths, profiles, variability). Especially, we present the possibilities to use the long-term optical monitoring
campaigns of variable AGNs in constraining the physics and structure of the BLR, and give some of the findings in two special objects. Here we outline our important conclusions:

i) We show that the Boltzmann-plot method can be exploited for the BLR plasma diagnostics, as it gives constraints to both the temperature and density of the BLR.

ii) The kinematics and geometry of the BLR is complex and most often there are contribution of more sub-regions with different geometry/motions to the total line profile. One possibility is that the BEL profiles can be described with the two-component model, where the disk-like region emission is contributing to the line wings, and an additional spherical component is producing the line core.

iii) The BLR physics is also complex, and there are most likely other ionization mechanism responsible for the line production, apart from the photoionization.

All of these findings should be taken into account when using the parameters of the BLR for the estimates of the mass of the supermassive black hole in the center of an AGN, and thus the investigations of the BLR properties are still in the top of the astrophysical research.

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