Physical properties of the broad line region in active galactic nuclei

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Abstract. We present here the study of the plasma in the broad line region (BLR) of active galactic nuclei (AGN). In order to probe the physical properties of the emitting plasma in the BLR we analyze the fluxes of the following broad emission lines (BELs): the hydrogen Balmer lines (Hα to Hε) and the helium lines from two subsequent ionization levels (He II λ4686 and He I λ5876). The BELs are obtained from the spectral synthesis photoionization code CLOUDY. We investigate these BELs in order to find conditions in the BLR where so-called Boltzmann-plot (BP) can be applied, and we found that in a number of modeled spectra it is working. We used these spectra to explore the dependence between plasma parameters (e.g. the averaged temperature, hydrogen density, etc.) and the ratio of He II λ4686 and He I λ5876 lines.

In this progress report we present our investigation of the emitting plasma in the BLR using the most intensive broad spectral lines in AGN spectra.

1. Introduction
Active galactic nuclei (AGN) are the most intriguing objects in the Universe, since they are the brightest and the most distant objects. The most accepted scenario of the structure of AGN is the one in which AGN are powered by the accretion of matter from the host galaxy onto super-massive black hole. One of the ways to study the inner emitting region of an AGN, closest to the black hole, is by analyzing its broad emission lines (BELs). These lines originate in the broad line region (BLR), which physics is still not fully understood (see e.g. [1, 2], for a review). It is obvious from the BEL fluxes and profiles that the physics and kinematics in the BLR is more complicated than in the narrow line region (NLR) or in gaseous nebulae, where we can use the forbidden line ratios for plasma diagnostics [3, 4].

Most of the BLR is photoionized. The definitive proof comes from the reverberation studies showing a direct response of the BEL fluxes to the continuum flux changes (see e.g. [5]). So far numerous papers have been dedicated to describe the BLR physics and explain its emitting spectrum using the photoionization models (see e.g. [5, 6, 7, 8], etc.). Even though there are roughly half a dozen large codes that are now highly improved, these numerical simulations still have some important unresolved problems related to the BLR [9]. One of the most interesting
problems is the observed small ratio between Ly$\alpha$ and H$\beta$ lines (usually in the range 5 - 15), while models predict much higher values (30 - 50) (see [10] and all references therein).

Moreover, the BLR is a kinematically and physically complex region and can be separated into at least two distinct regions according to the origin of the ”high-ionization lines” (HILs) and ”low-ionization lines” (LILs) (see e.g. [11, 1]), but also according to the observed complex line profiles of a single line that cannot be explained with a simple model (see e.g. [2, 12]). It is known that different BELs are produced over a wide range of distances from the central continuum source, and under very different physical conditions (see e.g. [2]). Therefore, collisional excitation, self-absorption, dust obscuration and complicated coupled line and continuum radiative-transfer problems should be taken into account when calculating the emission line spectrum, as well as the evident stratification of the BLR and its complex geometry.

2. Methods for plasma diagnostics

Spectroscopy, in general, offers different methods for diagnostics of emitting plasma (see e.g. [13]), but these methods could not be properly used to probe the physical conditions in the BLR of AGN. Particularly, it is difficult to find a direct method which would only use the observed BEL to determine the temperature and density in the BLR. There are some indications that the temperature should be less than 35,000 K due to the observed Fe II emission, as for the higher temperatures Fe II would be almost completely collisionally ionized to Fe III [13]. Note here that new investigations show that the Fe II emission is probably connected with an intermediate line region (see e.g. [14, 15], and references therein), therefore the problem of the temperature limit mentioned above should be taken with caution. Furthermore, there are some limits to the density obtained from the observed emission lines, i.e. due to the fact that the forbidden lines (e.g. [OIII] lines) are suppressed in the BLR, the lower limit for the electron density is roughly $n_e \approx 10^8 \text{cm}^{-3}$, while for the upper limit a critical density for collisional deexcitation of the broad lines of around $n_c \approx 10^{14} \text{cm}^{-3}$ can be used.

So far, there are only two proposed methods in the literature that include observations of the BELs to determine the BLR physical properties [16, 17]. Marziani et al. [16] 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 $9.5 < \log n_e < 12$. And since that ratio is correlated with the width of the broad H$\beta$ line, they gave a relationship for the estimates of the electron density in the BLR using either the ratio between these semi-forbidden lines or the width of the broad component of the H$\beta$ line [16]. Also, Laor [17] proposed a method that considers electron scattering influence on the line shapes and determines the physical parameters of the BLR by fitting the emission line exponential wings, in the case of the low luminosity AGN. The method assumes that the exponential wings are produced by the optically thin, isotropic, thermal electron scattering. In that case, by fitting the line wings with an electron-scattering model one can estimate the electron density and optical depth of the region [17]. However, the problem of this direct method for BLR diagnostics is that it can be applied only for the cases of the BEL profiles with exponential wings (e.g. the case of galaxy NGC 4395). Besides, another problem of this method is that kinematics of the emission gas in the BLR can strongly affect the BEL profiles.

On the other hand, Popović [18, 19] suggested that the Boltzmann-plot (BP) method, that is widely used in the laboratory plasma diagnostics [20], could be used in the case of the BLR of some AGN (see also [21, 22]). The BP method basically uses the flux ratios from one line series (as e.g. hydrogen Balmer line series) and the atomic parameters of the corresponding line series, to estimate the excitation temperature if the plasma is at least in the Partial Local Thermodynamical Equilibrium - PLTE [20]. The plasma is in PLTE if the populations of sufficiently highly excited levels are related to the next ion’s ground-state population by Saha-Boltzmann relations [23] or to the total population in all fine-structure levels of the ground-
Figure 1. The examples of AGN where BP method works (left panel) and where it does not give valid results (right panel), taken from [21]. Each panel contains the spectrum and the Boltzmann-plot applied on the line fluxes of the Balmer series. For the analysis, only the broad component of the Balmer lines was used. The wavelength is converted to the energy units (eV), but shifted for the energy of the lower level in the Balmer series $E_2$.

state configuration [20]. Moreover, the plasma in which PLTE exists for one series can be non-stationary and/or two-temperature plasma (for more details see [23]).

The Boltzmann-plot method is a well-known method for estimating the laboratory plasma excitation temperature [20, 24]. Starting from the assumptions that the emission line region is optically thin and that for one line series (as e.g. Balmer line series) the population of the upper energy states ($n \geq 3$) can be described with the Saha-Boltzmann distribution\footnote{We note here that since the emission deexcitation goes as $u \rightarrow l$ it is not necessary that level $l$ has the Saha-Boltzmann distribution.}, i.e. plasma is at least in the PLTE, we have that the flux $F_{ul}$ of the transition $u \rightarrow l$ can be written as [20, 25]

$$\log_{10}(F_n) = B - AE_u$$

(1)

where $F_n$ is the “normalized” line-flux with respect to the atomic constants which characterize the transition $F_n = \frac{F_{ul} \lambda}{g_u A_{ul}}$ (where $\lambda$ is the transition wavelength, $g_u$ is the statistical weight of the upper level, $A_{ul}$ is the transition probability), and $A = \log_{10}(e)/kT_{exc} \approx 5040/T_{exc}$ is the temperature indicator. Applying Eq. (1) to one line series and obtaining the value of the parameter $A$, we can estimate the excitation temperature of the region where these lines are originating (for more details on the BP method see [20] and for discussions on its application to the astrophysical plasma see [25, 22, 14]).

For some group of AGN (e.g. NGC 5548 or Mrk 817, see [22, 26]), it has been shown that the BP method could be applicable to the Balmer line series and might be used, at least roughly, to estimate the BLR physical properties [18, 22]. Fig. 1 gives an example of AGN where BP method works (left panel) and where it does not give valid results (right panel), taken from [21]. Each panel contains the AGN spectrum and the BP applied on the fluxes of the broad Balmer lines.

The question that comes naturally here is why BP works for some type 1 AGN and for some not? Therefore, the main motivation of this work is to investigate under which circumstances the BP method might be used to explore the physical conditions of the BLR, since photoionization is...
expected to control the plasma physical properties. Studying the BEL ratios, especially including the hydrogen Balmer lines (from Hα up to Hε), the HeII λ4686, and the HeI λ5876, we investigate the influence of BLR temperature and density, in order to assess whether particular combinations of these parameters can meet the fundamental assumptions of the BP method. To clarify this, we calculate several grids of numerical models, using the CLOUDY spectral synthesis code [27], to estimate the properties of the resulting spectra.

3. The numerical simulations

In order to investigate different BEL ratios, we generate grids of photoionization models of the BLR using the CLOUDY code (version C07.02.01: [27, 28]). Input parameters for the simulations are chosen to match the standard conditions in the BLR [28, 29, 8]. Assuming solar chemical abundances and constant hydrogen density, and using the code’s AGN template for the incident continuum shape (a continuum similar to the typical radio quiet active galaxies is chosen), we compute an emission-line spectrum for the coordinate pair of hydrogen gas density $n_{\text{H}}$ [cm$^{-3}$] and hydrogen-ionizing photon flux $\Phi_{\text{H}}$ [cm$^{-2}$s$^{-1}$]. The grid dimensions spanned over 4 orders of magnitude in each direction, from origin at log $n_{\text{H}} = 8$, log $\Phi_{\text{H}} = 17$ and with 0.2 dex increments, resulting with 441 simulations per grid. A column density $N_{\text{H}}$ [cm$^{-2}$] was kept constant while producing the grid of simulations. Many authors claim that the most probable value of the column density in the BLR is $N_{\text{H}} = 10^{23}$ cm$^{-2}$ (see e.g. [30, 29, 8]). Since the column density defines the optical thickness of the region, i.e. for higher column density the optical thickness in the emission lines increases, here we produce 5 different grids of models changing the column density in the range $N_{\text{H}} = 10^{21} - 10^{25}$ cm$^{-2}$. Therefore, the total number of simulations was 2205, i.e. 441 per grid.

Our further work on the results of the CLOUDY grids of models consists of an analysis of the emission line fluxes generated by the code. The code gives fluxes$^2$ of all lines formed in the emitting region with given chemical abundance, hydrogen density and hydrogen-ionizing photon flux. We consider in our analysis the hydrogen Balmer lines (Hα to Hε) and the flux ratio $R$ between the helium lines He II λ4686 and He I λ5876, defined as $R = F(\text{HeII}\lambda4686)/F(\text{HeI}\lambda5876)$, where $F$ is the line flux. We particularly consider these helium lines, since they are the lines of the same element but in two different ionization states, thus their ratio He II λ4686/He I λ5876 is sensitive to the change in the temperature and density [20]. Besides, these lines are in the same spectral range as Balmer lines. Additionally, from the grids of models we consider in our analysis an averaged temperature, which is the electron temperature averaged over the BLR radius ($T_{\text{av}}$ further in the text).

3.1. The analysis of the simulated BELs

For every grid of models, we analyzed the emission line fluxes generated by the code. The first step in analyzing the BEL ratios is to apply the BP method on the Balmer line ratios obtained by CLOUDY. Particularly, applying Eq. (1) we estimate the parameter $A$, from which we then calculate the BP temperature, i.e. the excitation temperature (hereinafter denoted as $T_{\text{BP}}$) of the region where Balmer lines are formed. Also, from the best-fitting of the normalized line ratios, we obtain the error of the BP fit (hereinafter denoted as $f$). In many cases a satisfactory fit of the Eq. (1) is not obtained, i.e. $f$ has pretty large values. This is more noticeable in the case of higher values of the hydrogen density and ionizing-photon flux, hence we plot the error of the BP fit $f$ in the hydrogen density vs. ionizing flux plane for all 5 grids of models (Fig. 2). In Fig. 2 we give only the contours inside which $f$ is less than 10%, 20% and 30%.

$^2$ The CLOUDY code gives all line fluxes normalized to the Hβ flux. Since it was not important for our analysis, we have used these values.
The best fitting results are summarized in Table 1. In the case of the low column density different column densities (totally ionized Boltzmann equation, should decrease with the electron density (in this case as hydrogen is nearly the helium lines represents the ratio of the two ionization states that, according to the Saha-dependence of hydrogen density on helium line ratio given in brackets. It can be seen from Fig. 3 that, even when the column density changes, the as around this value there is an obvious break. The best-fitting parameters for the solar chemical abundances, we take into account only models where this is valid is pretty constrained for different column densities (Fig. 2). Therefore, we introduced the constraint for our CLOUDY simulations that the error of the BP fitting of modeled spectra f is less than 10%.

Since we have photoionization as the main energy input mechanism and the assumption of the expected observational limit [31, 32] and an expected theoretical value for the ratio between HeII \( \lambda 4686 \) and HeI \( \lambda 5876 \) for the temperatures and densities we are using. The number of simulations that met our requirements within different uncertainty ranges was reduced to 22, 34, 54, 48, 73 for column densities \( N_H = 10^{21} - 10^{25} \text{cm}^{-2} \), respectively. From these we formed five sets of simulated spectra of single column density, labeled as e.g. CD21 for column density \( 10^{21} \text{cm}^{-2} \), etc. The models that satisfy these 3 constraints are represented with asterisks in Figure 2.

4. The relations between the BEL ratios and the BLR physical properties

We investigate in more details the five sets of simulated spectra defined above. First, we plot the average temperature \( T_{av} \) of the emitting region, one of the outputs of the model, with respect to the ratio \( R \) of the helium lines for all 5 sets (Fig. 3, left), and also the hydrogen density \( n_H \) versus the ratio \( R \) (Fig. 3, right). If the energy levels approximate a Saha-Boltzmann distribution, we expect the data sets to show a specific dependence on \( T_{av} \) and \( n_H \). We fit our data sets with the functions: \( T_{av} = A + B \cdot R \) and \( \log n_H = \frac{D}{(C+R)} \) where \( n_H \) is given in units of \( 10^5 \text{cm}^{-3} \). The best fitting results are summarized in Table 1. In the case of the low column density (\( N_H = 10^{21} \) and \( 10^{22} \text{cm}^{-2} \)), the samples were divided in two according to the limit \( R = 0.5 \), as around this value there is an obvious break. The best-fitting parameters for \( R > 0.5 \) are given in brackets. It can be seen from Fig. 3 that, even when the column density changes, the dependence of hydrogen density on helium line ratio \( R \) does not. Indeed, the ratio between the helium lines represents the ratio of the two ionization states that, according to the Saha-Boltzmann equation, should decrease with the electron density (in this case as hydrogen is nearly totally ionized \( n_e \approx n_H \)) as \( R \sim 1/n_e \) and increase with the temperature.

It can be seen in Fig. 2 that there is a certain regularity in the values of the input parameters \( \Phi_H \) and \( n_H \) for which the \( f \) is smaller than 10%. Therefore, the BP method could be considered valid if \( f \) is less than 10% (eventually 20% in the measured spectra) and that the parameter space where this is valid is pretty constrained for different column densities \( N_H \) (Fig. 2). Therefore, we introduced the constraint for our CLOUDY simulations that the error of the BP fitting of modeled spectra \( f \) is less than 10%.

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Figure 3. The average temperature $T_{av}$ of the emitting medium (left) and the hydrogen density (right) as the function of the ratio $R$ between the He II $\lambda 4686$ and He I $\lambda 5876$ lines, for five selected sets of simulated spectra of different column density $N_H = 10^{21} - 10^{25}$ cm$^{-2}$. The dashed line represents the best-fitting with the function $T_{av} = A_i + B_i \cdot R$ for the average temperature and $\log n_H = D_i/(C_i + R)$ for the hydrogen density. The name of the set is specified on each plot. In the case of the low column density ($N_H = 10^{21}$ and 10$^{22}$ cm$^{-2}$), the sample was divided and fitted separately for the average temperature.

Table 1. The best-fitting parameters $A_i$ and $B_i$ of the function $T_{av} = A_i + B_i \cdot R$, and $C_i$ and $D_i$ of the function $\log n_H = D_i/(C_i + R)$ for different column densities $N_H$. The best-fitting parameters for $R > 0.5$ are given in brackets.

| $\log N_H$ [cm$^{-2}$] | $A_i$ [K]   | $B_i$ [K] | $D_i$ [cm$^{-2}$] | $C_i$ [cm$^{-2}$] |
|------------------------|-------------|-----------|-------------------|-------------------|
| 21                     | 5556±102    | 4478±346  | 5.04±0.22         | 0.97±0.05         |
|                        | (-12533±7747) | (41351±13460) |                   |                   |
| 22                     | 4998±98     | 3801±300  | 3.76±0.17         | 0.70±0.04         |
|                        | (-3721±1939) | (21256±2872) |                   |                   |
| 23                     | 3486±200    | 7116±288  | 2.91±0.10         | 0.51±0.03         |
| 24                     | 4634±87     | 3326±134  | 2.37±0.10         | 0.40±0.03         |
| 25                     | 5208±119    | 1899±152  | 2.16±0.12         | 0.41±0.04         |
5. Discussion

In this progress report we give some results of our recent investigations of different broad line parameters (the flux ratios, EW, FWHM, etc.) in order to probe the physics of the BLR, i.e. the hydrogen Balmer lines (H\textalpha to H\epsilon) and the helium lines from two subsequent ionization levels (He II \lambda 4686 and He I \lambda 5876).

From the analysis of the hydrogen Balmer lines, we can say that the BP method gives valid results if the error of the BP fit $f$ is less than 10% (eventually 20% in the measured spectra). The parameter space of CLOUDY simulations where $f < 10\%$ is well constrained and in a similar range for different column densities $N_\text{H}$ (Fig. 2). This area of parameters contains lower ionizing fluxes and higher hydrogen densities, but depending on the column density the area increases keeping the same trend between the $n_\text{H}$ and $\Phi_\text{H}$. Therefore, for those parameters the BP method could be applied for the estimation of the excitation temperature. This indicates that for some physical conditions, even if we have the photoionization as the main heating process in the BLR, the hydrogen Balmer lines are produced in such way that they obey the Saha-Boltzmann equation, i.e. the BLR plasma is at least in the Partial Local Thermodynamical Equilibrium.

The physical parameters of the simulations for which the BP method could be applied ($f < 10\%$) follow some relations even when the column density changes. There is a linear relation between the average temperature $T_{\text{av}}$ of the emitting region and helium lines ratio $R$: $T_{\text{av}} = A + B \cdot R$ (Fig. 3, Table 1). Also, the hydrogen density depends on the helium line ratio $R$ as: $\log(n_\text{H}) = D/(C + R)$, where $n_\text{H}$ is given in the units of $10^7\text{cm}^{-3}$ (Figure 3, Table 1). Having in mind problems such as different emitting regions of helium and Balmer lines or the multicomponent origin of BELs, the relations given in Table 1 could be used as a rough estimate of the BLR physical parameters from direct measurements of the BELs.

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