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The line parameters and ratios as the physical probe of the line emitting regions in AGN

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A B S T R A C T

Here we discuss the physical conditions in the emission line regions (ELR) of active galactic nuclei (AGN), with the special emphasize on the unresolved problems, e.g. the stratification of the Broad Line Region (BLR) or the failure of the photoionization to explain the strong observed optical Fe II emission. We use here different line fluxes in order to probe the properties of the ELR, such as the hydrogen Balmer lines (Hα to Hε), the helium lines from two subsequent ionization levels (He II λ4686 and He I λ5876) and the strongest Fe II lines in the wavelength interval $\lambda\lambda$4400–5400 Å. We found that the hydrogen Balmer and helium lines can be used for the estimates of the physical parameters of the BLR, and we show that the Fe II emission is mostly emitted from an intermediate line region (ILR), that is located further away from the central continuum source than the BLR.

1. Introduction

Active galactic nuclei (AGN) are a ubiquitous phenomena, in a sense that most galaxies experience some sort of activity in their nucleus during their evolution. The most accepted scenario of the AGN structure is that they are powered by the accretion of matter onto a supermassive black hole (SMBH). One of the ways to study the inner emitting regions of an AGN, is by analyzing its emission lines, i.e. the broad (BELs) and narrow emission lines (NELs). So far many papers and textbooks are devoted to the physical properties of the emission line regions (ELR) see e.g. and references therein (Boroson and Green, 1992; Sulentic et al., 2000; Osterbrock and Ferland, 2006), but, there are still many open issues.

Spectroscopy, in general, offers different methods for diagnostics of the emitting plasma (see e.g. Griem, 1997; Osterbrock and Ferland, 2006), but these methods could not be properly used to probe the physical conditions in some ELR of AGN, as e.g. in the Broad Line Region (BLR), since the forbidden lines, that are usually employed in plasma diagnostics of the Narrow Line Region (NLR) or HII regions, are not present in the BELs spectrum. Particularly, it is difficult to find a direct method which would only use the observed BELs to determine the temperature and density in the BLR. On the other hand, the optical Fe II ($\lambda\lambda$4400–5400 Å) lines are one of the most interesting features in the AGN spectrum. The origin of the optical Fe II extreme emission and the geometrical place of the Fe II emission region in AGN, are still open questions. Also, there are many correlations of the Fe II lines and other AGN spectral properties which need physical explanation such as: EW Fe II vs. $\frac{\text{EW [O III]}}{\text{EW H}\beta}$, EW Fe II vs. peak [O III], EW Fe II and FWHM of Hβ, etc. (Boroson and Green, 1992).

In order to estimate the physical conditions (such as the temperature and hydrogen density) of the BLR we use the Balmer and helium line ratios obtained in two ways: (i) using the photoionization code CLOUDY, a spectral synthesis code designed to simulate conditions within a plasma and model the resulting spectrum, and (ii) extracting a sample of AGN from the Sloan Digital Sky Survey (SDSS) database. We investigate these line ratios in order to find conditions in the BLR where so-called Boltzmann-plot (BP) method is applicable (Griem, 1997; Popović, 2003, 2006a). For these special cases, we study the correlations between the average temperature, hydrogen density and He II/He I line ratio. Moreover, we present an investigation of the optical Fe II emission in AGN, for which we have used an additional sample of 111 AGN from the SDSS database. The strongest Fe II lines are identified and classified into four groups according to the lower level of the transition: ^{4}F,^{6}S,^{4}G and ^{2}D1. In this progress report, we report our recent investigations of the physical and kinematical properties of the BLR and Fe II emitting region. This report is organized as follows: in Section 2 we describe the numerical simulations of the BLR and briefly introduce the BP method, and give the analysis of the simulated BELs; in Section 3 we study the SDSS sample of hydrogen Balmer and helium lines, while in Section 4 the selection and analysis of the SDSS sample of Fe II lines are given; in Section 5

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we discuss some results and finally, in Section 6 our conclusions are given.

2. The BEL simulations

In order to study the BELs, we simulated the BLR emission line spectrum from different grids of the BLR photoionization models using the CLOUDY code version C07.02.01: (Ferland et al., 1998; Ferland, 2006). Input parameters for the simulations are chosen to match the standard conditions in the BLR (Ferland, 2006; Korista and Goad, 2000, 2004), i.e. the solar chemical abundances, the constant hydrogen density, the code's AGN template for the incident continuum shape. We compute an emission-line spectrum for the coordinate pair of hydrogen gas density $n_{\rm H}$ [cm^{-3}] and hydrogen-ionizing photon flux $\Phi_{\rm H}$ [cm^{-2} s^{-1}]. The grid dimensions spanned four orders of magnitude in each direction, and with an origin of $\log n_{\rm H} = 8$, $\log \Phi_{\rm H} = 17$ was stepped in 0.2 dex increments. A column density $N_{\rm H}$ [cm^{-2}] was kept constant in producing one grid of simulations. Even though many authors claim that the most probable value of the BLR column density is $N_{\rm H} = 10^{23}$ cm^{-2} (Dumont et al., 1998; Korista and Goad, 2000, 2004), we produce here five different grids of models changing the column density in the range $N_{\rm H} = 10^{21}$–10^{25} cm^{-2}.

We further analyze the BEL fluxes[1] from the CLOUDY grids of models. We consider in our analysis the hydrogen Balmer lines (Hα to Hε) and the flux ratio R of the helium lines He II λ4686 and He I λ5876, defined as $R = F(\text{He II } \lambda 4686)/F(\text{He I } \lambda 5876)$, 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 (see e.g. Griem, 1997). 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 ($T_{\rm av}$ further in the text).

2.1. The Boltzmann-plot method for excitation temperature diagnostics

For the plasma of the length ℓ that emits along the line of sight, assuming that the temperature and emitter density does not vary too much, the flux F_{ul} of a transition from the upper to the lower level ($u \rightarrow l$) can be calculated as (Griem, 1997; Popović, 2003, 2006a; Popović et al., 2008)

$$F_{ul} = \frac{hc}{\lambda} g_u A_{ul} \frac{N_0}{Z} \exp(-E_u/kT)\ell,$$

where λ is the transition wavelength, g_u is the statistical weight of the upper level, A_{ul} is transition probability, N_0 is the averaged total number density of radiating species which effectively contribute to the line flux (which are not absorbed), Z is the partition function, E_u is the energy of the upper level, T is the averaged excitation temperature, and h, c and k are the Planck constant, the speed of light, and the Boltzmann constant, respectively. The additional assumption made here is that the population of the upper level in the transition follows the Saha–Boltzmann distribution for more detailed derivation check (Popović et al., 2008). From the above equation comes the so-called Boltzmann plot (BP) that can be used to estimate the excitation temperature $T_{\rm exc}$ in the BLR

$$\log_{10}(F_n) = \log_{10} \frac{F_{ul} \cdot \lambda}{g_u A_{ul}} = B - A E_u,$$

where B and A are BP parameters, and $A = \log_{10}(e)/kT_{\rm exc} \approx 5040/T_{\rm exc}$ is the temperature indicator. Therefore, for one line series (as e.g. Balmer line series) if the population of the upper energy states ($n \geqslant 3$)[2] can be described with the Saha–Boltzmann distribution, then by applying the last equation to that line series and obtaining the value of the parameter A, we can estimate the excitation temperature of the region where these lines are originating. We should emphasize that the additional assumption in the BP method is that the Balmer lines are originating in the same emitting region.

In spite of the fact that the BP method has some obvious advantages, i.e. it is only using the measured Balmer line fluxes, that are easily observed, to estimate the excitation temperature, one should take into account some possible problems that could occur when using the emission line to determine the BLR physical properties: (i) the line profiles are usually very complex and indicate that more than one component contribute to the total line flux, therefore one should be aware of the multi-component BLR structure when estimating the BEL fluxes; (ii) the Balmer lines do not have to necessarily originate in the same region, e.g. there some indications that the Hα and Hβ line are forming in two distinct regions since it has been shown that the Hβ line is systematically broader than Hα (Shapovalova et al., 2008); (iii) there are different mechanisms contribution to the line formation. The photoionization seems to be working well, but other heating mechanisms should be taken into account.

2.2. The analysis of the simulated BELs

The first step in analyzing the BEL ratios is to apply the BP method on the Balmer line ratios given by CLOUDY to estimate the parameter A, from which we then calculate the BP temperature, i.e. the excitation temperature ($T_{\rm BP}$ further in the text) 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 (f further in the text). A few examples of the BP applied on the Balmer lines simulated with CLOUDY for column density of $N_{\rm H} = 10^{23}$ cm^{-2} are presented in Fig. 1. In many cases a satisfactory BP fit 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 five grids of models of different column density in Fig. 2 (only the contours inside which f is less than 10%, 20% and 30% are given). From Fig. 2 can be seen that if the BP method could be considered valid if f is less than 10% (eventually 20% in the measured spectra) the parameter space where this is valid is pretty constrained for all column densities $N_{\rm H}$.

Out of all photoionization models, we select just those that follow these constraints: (i) the error of the BP fit f less than 10%, (ii) the average temperature $T_{\rm av}$ less than 20,000 K, as for larger temperatures the Balmer line ratios are not sensitive to the temperature changes and the BP method cannot be applied (Popović, 2006b), and (iii) the ratio of helium lines R less than 2. Following this criteria, we constructed five samples of simulated BELs, of single column density, labeled as e.g. CD21 for column density $N_{\rm H} = 10^{21}$ cm^{-2}, etc. The models that satisfy these three constraints are represented with asterisks in Fig. 2.

2.3. The correlations 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 $T_{\rm av}$ of the emitting region, one of the outputs of the model, with respect to

[1] The CLOUDY code gives all line fluxes normalized to the Hβ flux. Since it has no influence in our analysis, we have used these values.

[2] We note here that since the emission de-excitation goes as $u \rightarrow l$ it is not necessary that level l has the Saha–Boltzmann distribution.