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Invited review

THE BROAD LINE REGION OF AGN: KINEMATICS AND PHYSICS

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SUMMARY: In this paper a discussion of kinematics and physics of the Broad Line Region (BLR) is given. The possible physical conditions in the BLR and problems in determination of the physical parameters (electron temperature and density) are considered. Moreover, one analyses the geometry of the BLR and the probability that (at least) a fraction of the radiation in the Broad Emission Lines (BELs) originates from a relativistic accretion disk.

Key words. Galaxies: active – Galaxies: nuclei – Atomic processes – Line: profiles – Plasmas

1. INTRODUCTION

A group of galaxies emits intense permitted and forbidden lines from the central part where a massive black hole is supposed to be located. This type of galaxies, so called Active Galactic Nuclei (AGN), are known as a most powerful sources of radiation in the Universe.

The investigation of nature of the emitting ionized gas in galactic nuclei is one of important subjects in astrophysics today. Firstly, investigating the processes in the central parts of these objects we can learn about the innermost parts of other 'normal' galaxies. Secondly, AGN are the most powerful sources, located at different cosmological time-scales, and their investigation is cosmologically important. Finally, a part of emission from these objects (e.g. in the X-rays) has its origin very close to a massive black hole, and investigation of this emission can help us understand the physical processes in a strong gravitational field.

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 originate from 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 (the so called Broad Line Region - BLR) in the central part of AGN (Osterbrock 1989, Krolik 1999, Peterson 2003). The BELs can be emitted by highly and lowly ionized emitters (so called High Ionization Lines - HILs and Low Ionization Lines - LILs). The investigation of BEL shapes provide information about conditions of the emitting gas surrounding a massive black hole, assumed to be in the center of these objects.

Indirect techniques such as reverberation mapping (e.g. Peterson 1993) can, in principle, provide information concerning the spatial distribution of the emitting gas, but in practice require long monitoring campaigns and are often inferred by technical and interpretation difficulties (e.g. Peterson et al. 1999). Whilst these studies appear to favor Keplerian dynamics, it is unclear whether or not the gas distribution has axial or spherical symmetry (e.g. Kaspi et al. 2000). Spectropolarimetry provides an alternative approach to investigate the nature of the BLR (see e.g. Smith et al. 2005). The unique diagnostic strength of this technique is that the polarization state of scattered light carries the imprint of the scattering geometry, allowing the structure and kinematics of both the scattering medium and the emission source to be investigated in unresolved sources. Moreover, spectropolarimetry provides us an evidence that in some Sy 2 galaxies the BLR is present (e.g. in the case of Mrk 533, see Miller and Gooldrich 1990).

Besides the strong emission lines, in spectra of the AGN with BELs, the Broad Absorption Lines (BAL) in the UV part of spectra are present. Approximately 10% of all quasars are with broad, blueshifted absorption lines. The outflow velocity can reach 0.1-0.2 c. Usually, in their spectra the high ionization species as C IV λ1549, Si IV λ1397, N V λ1240 and Lyα lines have been observed. Rarely some of them also exhibit broad absorption lines of Mg II λ2798 and Al III λ1857, low ionization lines. Broad absorption lines may have different shapes, and also differences in continua are present in spectra of various types of these objects (see e.g. Reichard et al. 2003). The spectrum of a Broad Absorption Line Quasar (BALQSO) is usually interpreted as a superposition of the continuum emission from the central engine with broad emission lines from the BLR created near the center of a QSO and the broad absorption lines emitted from a separate outlying region - Broad Absorption Line Region (BALR).

In at least four last decades, a large number of papers about the BLR structure has been published (see e.g. review of Sulentic et al. 2000, Dultzin-Hacyan et al. 2000); also, a unified model of all AGN was proposed and discussed (e.g. Antonucci 1993, Elvis 2000, Lípari and Terlevich 2006). But some unanswered questions concerning the BLR are still present:

(i) **Physics of the BLR**. Since the BLR is located on a relatively small distances from the extremely powerful energy source of AGN, the matter in the BLR is likely to be in a physical environment which can hardly be compared to that in other well studied astrophysical objects. It seems that plasma in the BLR is in a condition that is closer to stellar atmospheres than to photoionized nebulae (Osterbrock 1989). As a direct consequence, many of the custom any techniques, that have been derived to identify the physical properties of photoionized nebulae, are often unable to provide reliable answers or even to be applied in the case of the BLR. Some approximation methods can be applied to probe the physics of the BLR, but they are still far from taking us to a detailed solution. Also, the connection between BALR and BLR is not clear. Very broad absorption lines in the UV spectra of AGN indicate that they should originate close to the AGN engine, but it is not clear yet where this region is placed, closer to or further away from the BLR, or even a part of the BLR is in such a condition that it is able to absorb radiation in the UV.

(ii) **Kinematics of the BLR**. The strong gravitation field is often taken into account in order to constrain the geometry of the BLR, but the true BLR geometry is not yet clearly known. There is a small fraction of AGN with double peaked broad lines which indicate presence of an accretion disk in the BLR, but the number of such objects is statistically insignificant (around 5%) for conclusion about the disk presence. On the other hand, various geometries can be considered (spherically distributed clouds, jets, etc.). Also, it is not clear if the BLR is composed of more than one geometrically consistent region, or it is a combination of two or even more geometrically different regions (e.g. disk+jets, or spherical region+disk, etc.).

In this review, we will give some ideas about physics and kinematics of the BLR. The aim of the paper is to give an overview of the investigation of the BLR physics and kinematics, especially the investigation that were carried out by our group.

2. BROAD LINE REGION: KINEMATICS

Various geometries can be assumed in describing the BLR (see Sulentic et al. 2000 in more details). The BLR geometry (kinematics) affects the broad line shapes. We should note here that due to high random velocities (about several thousand km/s) we can expect that Doppler effect is dominant among other broadening mechanisms (broadening due to collisions, natural broadening, etc.). Therefore, in order to grasp the BLR kinematics, in first approximation one can fit the broad lines with a number of Gaussin functions (see Figs. 1 and 2). First step in the investigation of the BEL shapes is to clean a BEL from the narrow and satellite lines.

The rotating accretion disk model (see e.g. Perez et al. 1988, Chen et al. 1989, Chen and Halpern 1989, Dumont and Collin-Suffrin 1990ab, Dumont et al. 1991, Dumont and Joly 1992, Eracleous and Halpern 1994, 2003, Sulentic et al. 1998, Pariev and Bromley 1998, Rokaki and Boisson 1999, Shapovalova et al. 2004, Popović et al. 2001a, 2002, 2003a, 2004, Kollatschny and Bischoff 2002, Bon et al. 2006) has been very often discussed in order to explain the observed broad optical emission-line profiles in AGN. This model fits well the widely accepted AGN paradigm that the "central engine" consists of a massive black hole fueled by an accretion disk. However, the fraction of AGN clearly showing double-peaked profiles is small and statistically insignificant (e.g. Strateva et al. 2003). On one hand, the presence of double-peaked lines is not required as a necessary condition for the existence of a disk geometry in BLRs. Even if the emission in a spectral line comes from a disk, the parameters of the disk (e.g. the inclination) can be such that one observes single-peaked lines (e.g. Popović et al. 2004, Ilić et al. 2006). Also, a Keplerian disk with disk wind can produce single-peaked broad emission lines as normally seen in most of the AGN (Murray and Chang 1997). On the other hand, taking into account the complexity of emission line regions of AGN (see e.g. Sulentic et al. 2000), one might expect that the broad emission lines are composed of radiation from two or more kinematically and physically different emission regions, i.e. that multiple BLR emission components with fundamentally different velocity distributions are present (see e.g. Romano et al.

1996). Consequently, one possibility could be that the emission of the disk is masked by the emission of another emission line region. Recently, in several papers (Popović et al. 2001a, 2002, 2003a, 2004, Bon et al. 2006, Ilić et al. 2006) the possibility that the disk emission is present in the AGN having single peaked lines is investigated and one can conclude that it is likely that the disk emission mainly contributes to the wings of BELs. This supports the idea that the broad optical lines originate in more than one emission region, i.e. that the Broad Line Emission Region is complex and composed of at least two regions (e.g. Ilić et al. 2006). Note here that Corbin and Boroson (1996) found that 'the difference between the Lyα and Hβ full width at zero intensity (FWZI) values provides additional evidence of an optically thin very broad line region (VBLR) lying inside an intermediate line region (ILR) producing the profile cores'. Consequently, one may expect that the VBLR can be formed in a disk or disk-like emission region.

2.1 Two-component model of the BLR

As we mentioned, Corbin and Borson (1996) investigated the combined ultraviolet and optical spectra of 48 QSOs and Seyfert 1 galaxies in the redshift range 0.034-0.774. They found a statistically significant difference between the FWZI distributions of the Lyα and Hβ lines. The difference between the Lyα and Hβ FWZI values provides additional evidence for an optically thin VBLR (which might be a disk or disk-like region) which contributes to the line wings. It is located inside an ILR which produces the profile cores. Also, they found a relatively weak correlation between the UV profile asymmetries and widths and those of the Hβ line. This suggests a stratified structure of the BLR, consistent with the variability studies of Seyfert 1 galaxies (see e.g. Kollatschny 2003). The smaller average FWHM values of the UV lines compared to the Hβ indicate that the ILR emission makes a higher contribution to the UV lines, whereas in the Balmer lines the VBLR component is more dominant. This is also the case in well known AGN with double-peaked Balmer lines, which usually show a single-peaked Lyα line (see e.g. the case of Arp 102B, Halpern et al. 1996).

The wings of the broad Hα emission line in the spectra of a large sample of AGN (around 100 spectra) were also investigated by Romano et al. (1996). They found an indication of multiple BLR emission. Although a two-component model can probably be represented by other geometries, we choose the one with a disk giving the wings of the lines, and a spherical component giving the core of the line. We assume that the kinematics of the additional emission region can be described as the emission of a spherical region with an isotropic velocity distribution, i.e. with a local broadening w_G and shift z_G. Consequently, the emission line profile can be described by a Gaussian function. The whole line profile can be described by the relation (Popović et al. 2004):

$$I(\lambda) = I_{AD}(\lambda) + I_G(\lambda)$$

where $I_{AD}(\lambda)$, $I_G(\lambda)$ are the emissions of the relativistic accretion disk and of an additional region, respectively. The model capable reproducing broad line profiles (see Fig. 3), but the problem is the number of needed parametes which cannot be constrained properly (see discussion in Popović et al. 2004 and Bon et al. 2006).

We should mention that besides a disk (or a disk-like region) or spiral shock waves within a disk (Chen et al. 1989, Chen and Halpern 1989), other geometries may cause the same kinds of substructure

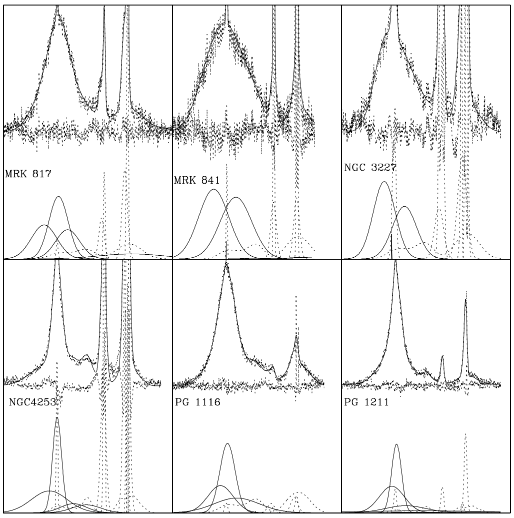

Fig. 1. *Gaussian multicomponent analysis of the emission lines indicates very complex kinematics of the BLR and NLR (Popović et al. 2004).*

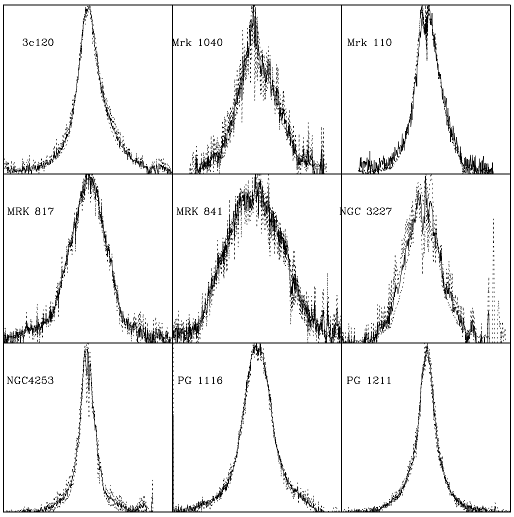

Fig. 2. *The broad line profiles after subtraction of the narrow and satellite lines (Popović et al. 2004).*

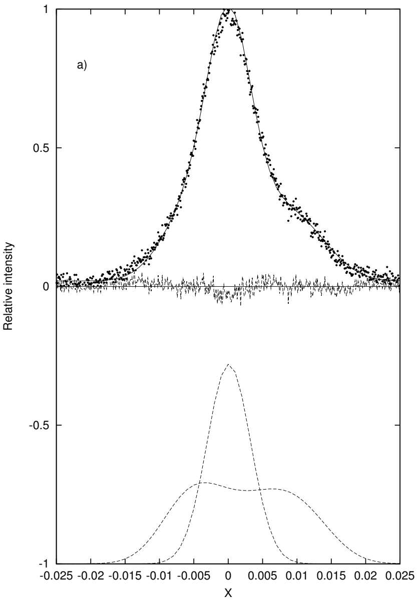

Fig. 3. *Two-component model fit of the broad emission line: below are the components corresponding to the line core and wings. The double peaked component that predominantly contributes to the line wings is assumed to be emitted from an accretion disk (Popović et al. 2004).*

in the line profiles: i) emission from the oppositely-directed sides of a bipolar outflow (Zheng et al. 1990, 1991); ii) emission from a spherical system of clouds in randomly inclined Keplerian orbits illuminated anisotropically from the center (Goad and Wanders 1996); or iii) emission from a binary black hole system (Gaskell 1982, Gaskell 1996, Popović et al. 2000). In any case, one should consider a two-component model with an ILR contributing to the broad line cores and one additional emitting region contributing to the broad line wings. Recent investigations (see e.g. Wang et al. 2003, Eracleous and Halpern 2003) have shown that the disk geometry for VBLR may be accepted as a reality. Moreover, Eracleous and Halpern (2003) found that the disk emission is more successful not only in explaining double-peaked line profiles but also in interpreting another spectroscopic properties of AGN presenting these double-peaked Balmer lines.

2.2 Investigation the BLR geometry by gravitational microlensing

Gravitational lensing is in general achromatic: the deflection angle of a light ray does not depend on its wavelength. However, the wavelength-dependent geometry of the various emission regions may result in chromatic effects (see Popović and Chartas 2005, and references therein). Studies aimed at determining the influence of microlensing on spectra of lensed quasars (hereafter QSOs) ought to account for the complex structure of the QSO central emitting region. Since the sizes of the emitting regions are wavelength-dependent, microlensing by stars in a lens galaxy will lead to a wavelength-dependent magnification. The geometries of the line and the continuum emission regions are, in general, different and there may exist a variety of geometries depending on the type of AGN (i.e. spherical, disc-like, cylindrical, etc.). Observations and modeling of microlensing of the BLR of lensed QSOs are promising, because the study of the variations of the BEL shapes in a microlensed QSO image could constrain the size of the BLR and the continuum region.

Continuum-line reverberation experiments with low-redshift QSOs tell us that the broad-emission line region (BLR) is significantly smaller than earlier assumed, and it is typically several light days up to a light year across (e.g., Kaspi et al. 2000). It means that the BLR radiation could be significantly amplified due to microlensing by (star-size) objects in an intervening galaxies (Abajas et al. 2002, 2005). Hence, gravitational lensing can provide an additional method for studying the inner structure of high-redshift quasars for several reasons:

(i) the extra flux magnification, from a few to 100 times, due to the lensing effect enables us to obtain high signal-to-noise ratio (S/N) spectra of distant (high-redshifted) quasars with less observing time;

(ii) the magnification of the spectra of the different images may be chromatic (e.g. Popović and Chartas 2005, Popović et al. 2006ab, Jovanović 2006) since the spectral line and the continuum emitting regions are different in sizes and geometrically complex and/or complex gravitational potential of lensing galaxy; (iia) consequently, microlensing events lead to wavelength-dependent magnifications of the continuum that can be used as indicators of their presence (Popović and Chartas 2005);

(iii) gravitational microlensing can also change the shape of the broad lines (see Popović et al. 2001b,c, Abajas et al. 2002, 2005, Popović and Chartas 2005), the deviation of the line profile depends on the geometry of the BLR.

Finally, the monitoring of lensed QSOs in order to investigate the effect of lensing on the spectra can be useful not only for constraining the unresolved structure of the central regions of QSOs, but also for providing insight into the complex structure of the lens galaxy.

Taking into account the redshift of lensed QSOs, one ought to obtain the spectra from 3500 to 9000 Å (covering also, the broad C IV, CIII and Mg II lines which are emitted from the BLR region) of a sample multi-imaged QSOs. Concerning the estimation of the BLR dimensions (see Kaspi et al. 2000), one should select a sample of lensed QSOs where the BLR microlensing might be expected (Abajas et al. 2002). To find the possible microlensing one can apply the method given by Popović and Chartas (2005) comparing the spectra (in the continuum and in the broad lines) of different components in order to detect the difference caused by microlensing or/and millilensing. Using previous theoretical estimates of line shape variations due to microlensing (Popović et al. 2001bc, Abajas et. al. 2002, 2005, Popović and Chartas 2005, Popović et al. 2003a,b, 2006ab, see also Fig. 4), the observed spectra can be fitted to the theoretical line profile, assuming different geometries. Thence, one will be able to estimate the geometry and dimension of the BLR. Also, comparing difference in amplifications, of the continuum, C IV and Mg II lines one will be able to conclude about differences between high and low ionized line emitting regions and compare them with the size and geometry of the continuum emission region.

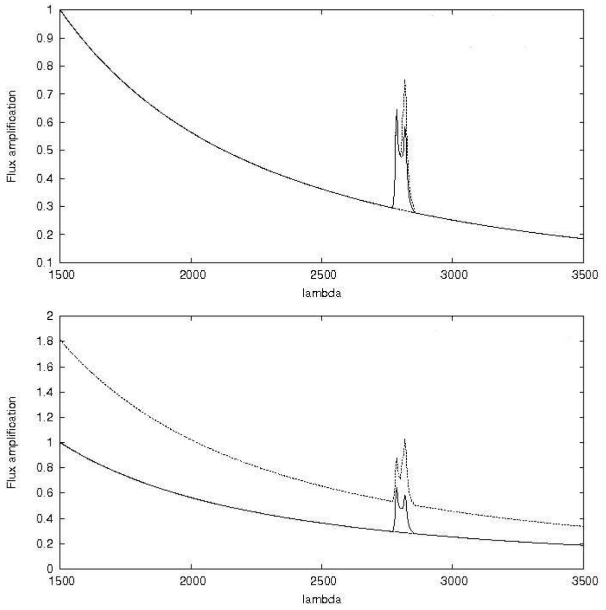

Fig. 4. *The simulation of the variation in Mg II,* $\lambda = 2798\mathring{A}$ *and the continuum between 1500 Å and 3500 Å due to microlensing by straight fold caustic. The microlensing may affect only line profile (top) as well as the line profile and the continuum (down). Amplified spectra is presented by dashed line (Popović 2005).*

As an example, let us discuss the variability in the shape of Mg II line of images A and B of J0924+021 observed in two epochs (on 14/01/2005 and 01/02/2005) by Eigenbrod et al. (2006).

Comparing the Mg II line shapes of components A and B, we concluded that the shape of Mg II was changed in the A image observed on 01/02/2005. There is no significant difference between line profiles of Mg II lines observed on 14/01/2005 between A and B components (only they are amplified by different factor due to lensing effect). Also, there is no significant difference between line profiles of the component B observed on 01/02/2005 and 14/01/2005. We used test described in Popović and Chartas (2005), and found that it was probably microlensing that caused this variation, as it was noted also in Eigenbroad et al. (2006). To explain this, we apply the two component model, assuming that only the disk is microlensed (due to microlening with Einstein Radius Ring at about several thousand gravitational radii). As one can see in Fig. 5, the model can explain registred changes in the line profile from the two epochs. Note here that the similar variation in the line profiles of lensed QSO SDSS J1004+4112 was reported by Richards et al. (2004), Lamer et al. (2006) and Gómez-Álvarez et al. (2006).

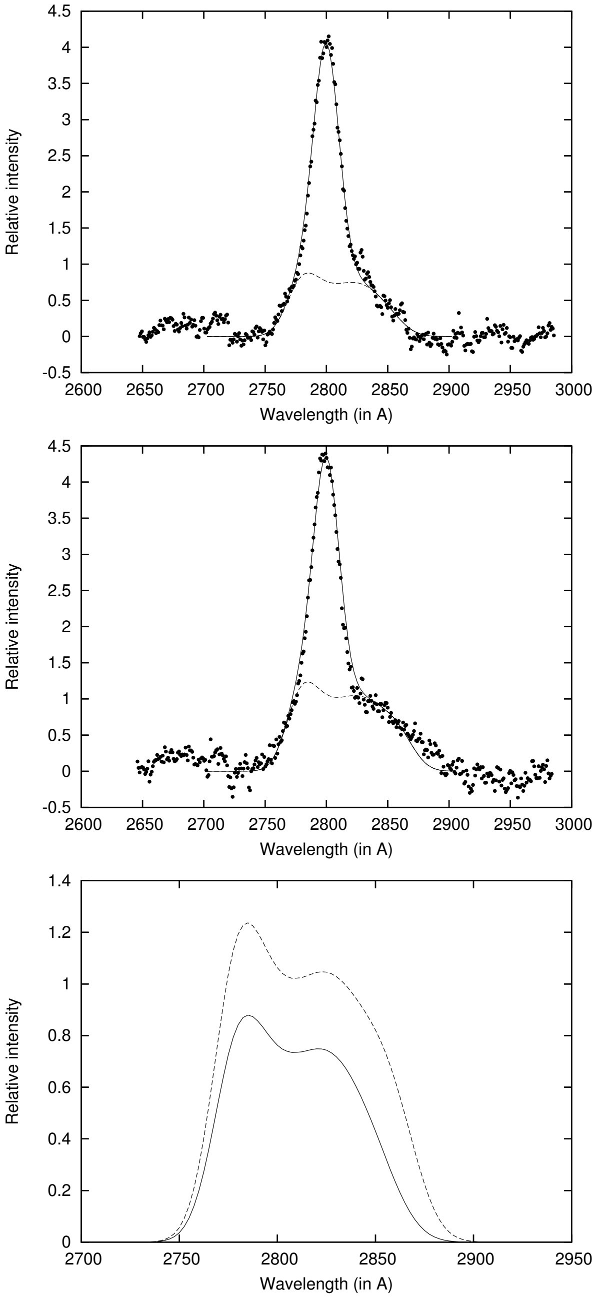

Fig. 5. *The best fit with the two-component model non-amplified line (up) and after including microlensing of the disk, amplified line (middle). Down is shown the comparison the non-amplified disk emission line (solid line) with amplified (dashed line).*

3. PHYSICS OF THE BLR: DIAGNOSTIC BY USING EMISSION LINES

Physics and kinematics in the Broad Line Region are more complicated than in the Narrow Line Region (NLR) or in gaseous nebulae (Osterbrock 1989, Krolik 1999, Sulentic et al. 2000 and references therein). In contrast to the NLR where forbidden lines (e.g. [OIII] and [NII] lines[1]) can be used as emitting plasma diagnostics, the physical conditions in the BLR cannot be understood using simple relations between the line ratios. The pure recombination conditions cannot be applied in the BLRs, e.g. the flux line ratios are different from those expected in the case of recombination (e.g. in some AGN $Ly\alpha/\mathrm{H}\beta \approx 10$, Osterbrock 1989). Moreover, the optical spectrum of many AGN is dominated by two broad permitted Fe II emission line blends, one centred at about 4570 Å and the other centred at 5350 Å. Optical Fe II has now been measured in the spectrum of several hundred broad-line AGN, showing a large range of intensity relative to Balmer recombination lines. From the theoretical point of view, considerable efforts have been devoted to understanding the origin of Fe II optical emission in broad-line AGN during the last few decades. However, extreme Fe II emission is not well explained by standard photoionization models. There are several ideas about the source of heating for the Fe II emitting gas (as e.g. zones of the BLR of very high opacity to ionizing radiation, see Kwan and Krolik 1981; jets responsible for the compact radio sources, see Norman and Miley 1984), but one can also indicate collisional ionization process (Joly 1988, 1989, 1991, Véron-Cetty et al. 2006), which could be related mainly to shocks.

Several effects can result in such a ratio of the line flux of hydrogen (and another AGN) lines[2] between them, also the collisional excitation and extinction effects. Dust is present in the host galaxy of an AGN (see e.g. Crenshaw et al. 2002, Crenshaw et al. 2004, Gabel et al. 2005, etc.), but it seems that in some cases it cannot explain the line flux ratios. Also, in the BLR different mechanisms capable of affecting the spectral lines can be present. The classical studies point toward photoionization as the main heating source for the BLR emitting gas (see e.g. Kwan and Krolik 1981, Osterbrock 1989, Baldwin et al. 1995, Marziani et al. 1996, Baldwin et al. 1996, Ferland et al. 1998, Krolik 1999, Korista and Goad 2004) that may explain observed spectra of AGN. But, in some cases as e.g. in Dumont et al. (1998) and Véron-Cetty et al. 2006, a favor is given to a non-radiatively heated region that contributes to the BLR line spectrum. Therefore, photoionization, recombination and collisions can be considered as relevant processes in BLRs. At larger ionization parameters, recombination is more important, but at the higher temperatures the collisional excitation becomes also important as in the case of low ionization parameters (Osterbrock 1989). These two effects, together with the radiative-transfer effects in Balmer lines, should be taken into account in explaining the ratios of Hydrogen lines. Moreover, the geometry and possible stratification in the BLR may also affect both continuum and line spectra (Goad et al. 1993).

Notice here that in investigation of the physical parameters of the BLR, first a theory is assumed (i.e. model of excitation, absorption of radiation, energy output from the center, etc.) and thereafter a comparison between the observed and the predicted line ratios is discussed. There is a problem to develop a theory that can be applied to observations, i.e. to use the measured line ratios or line profiles to directly conclude about the physical parameters or physical conditions in the BLR.

To conclude about physics in the BLR it is very useful to compare emission-line flux ratios with photoionization models. But also recently two methods are given that can be also used in determination (indication) of physical parameters in the BLR: (i) BP method given by Popović (2003, 2006) using the Balmer lines flux ratios and atomic parameters of Balmer lines, and (ii) electron scattering influence on line shapes given by Laor (2006) where the physical parameters can be determined by fitting the line wings.

3.1 Photoionization models

First approach to use the photoinoization model started from assumption of the existence of a single cloud pressure law with radius (e.g. Rees et al. 1989). The simple one-zone photoionization models cannot properly describe BLRs since one can expect that gas clouds in BLRs embrace wide ranges in densities and/or ionization degrees in general (see e.g. Collin-Souffrin et al. 1982). In order to investigate the physical properties of gas clouds in the BLR, Baldwin et al. (1995) proposed the Locally Optimally emitting Cloud (LOC) model, that is a multizone photoionization model. In this model, gas clouds with a wide range of physical conditions are present at a wide range of distances, and thus the net emission-line spectra can be calculated by integrating in the parameter space of gas density and radius, assuming different distribution functions. Using this model one can calculate fluxes of both low-ionization emission lines and high-ionization emission lines consistently and simultaneously. It can be used to investigate physical properties of ionized gas clouds in the BLR (e.g. Korista and Goad 2004). Using the method, one can obtain the net emission-line flux by integrating the line emissivity of all clouds

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[1] These lines also can be used to check sophisticated calculation of atomic parameters, see e.g. Dimitrijević et al. (2006)

[2] In the last over 30 years, there appeared numerous papers devoted this problem, see e.g. Netzer (1975, 1976), Ferland and Netzer (1979), Ferland et al. (1979), Kwan (1984), Kallman and Krolik (1986), Collin-Souffrin (1986), Collin-Souffrin and Dumont (1986), Rees et al. (1989), Ferland et al. (1992), Shields and Ferland (1993), Dumont et al. (1998), etc.

$$L_{\rm line} = \int\int 4\pi r^2 F_{\rm line}(r,n) f(r) g(n) dn dr \,,$$

where $f(r)$ and $g(r)$ are the cloud distribution function and gas density, respectively. The radius of the BLR is specified by the ionizing photon flux. Baldwin et al (1995) assumed simple power-law functions for both $f(r) \sim r^{\Gamma}$ and $g(r) \sim n^{\beta}$. It is shown that the BLR emission line spectra may be well reproduced by the LOC models with $\Gamma \approx -1$ and $\beta \approx -1$ (Korista and Goad 2000). The problem with model is, as mentioned above, that in some cases photoionization models cannot explain well the flux ratios in some BELs (broad hydrogen lines as well as Fe II lines).

3.2 Using the Balmer line ratios: the BP method

Recently, Popović (2003, 2006) showed that in the BLR of some AGN, the Balmer line ratios follow the Boltzmann-plot (BP).

If we assume that plasma of the length ℓ along the line of sight emits, the flux (or the spectrally integrated emission-line intensity (I_{lu})) can be calculated as:

$$I_{lu} = \frac{hc}{\lambda} g_u A_{ul} \int_0^{\ell} N_u(x) dx \qquad (1)$$

where λ is transition wavelength, g_u statistical weight of the upper level, A_{ul} transition probability, N_u is the number of emitters excited in upper level which effectively contribute to the line flux (which are not absorbed) and h and c are the well known constants (Planck and speed of light). In principle, the N_u can be inhomogeneous across the line of sight and, also, the radiative self-absorption can be present. But, assuming that populations in the observed region (in all layers) follow the Boltzmann-Saha distribution one can write

$$N_u(x) \approx \frac{N_0(x)}{Z} \exp(-E_u/kT_e(x)), \qquad (2)$$

where Z is the partition function, N_0 the total number density of radiating species, E_u the energy of the upper level, T_e electron temperature and k the Boltzmann constant.

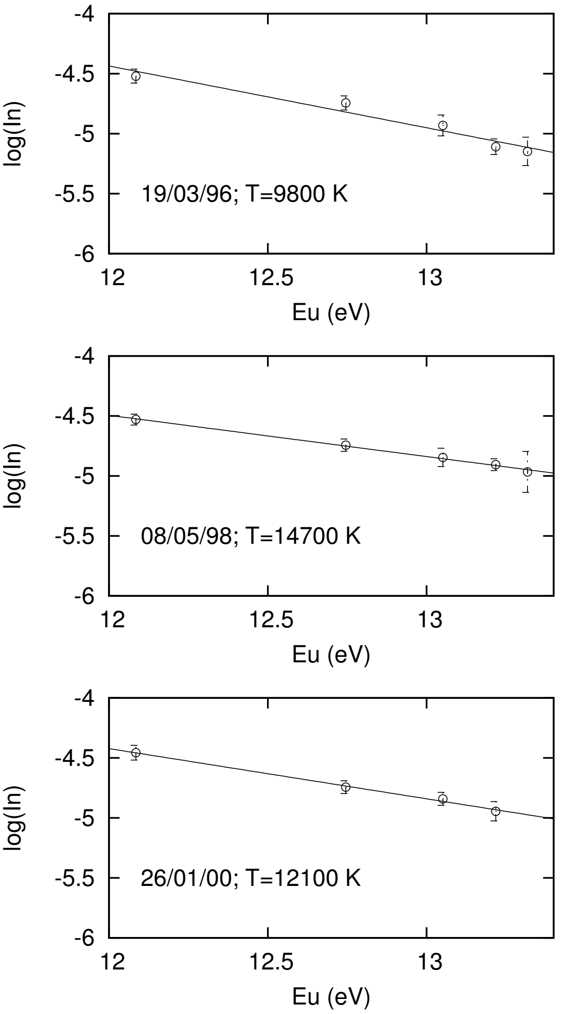

Fig. 6. *The Boltzmann Plots of the Balmer line series of NGC 5548 from different periods (Popović et al. 2006c).*

In the case of optically thin plasma with relatively small variations in electron density and temperature, one can write (see e.g. Griem 1997, Konjević 1999)

$$I_{lu} = \frac{hc}{\lambda} g_u A_{ul} \int_0^{\ell} N_u dx$$

$$\approx \frac{hc}{\lambda} A_{ul} g_u \ell \frac{N_0}{Z} \exp(-E_u/kT_e), \qquad (3)$$

where T_e is electron temperature. For one line series (e.g. the Balmer line series), if the population of the upper energy states ($n \geq 3$)[3] adhere to a Boltzmann distribution that one can determine their excitation temperature (T_e) that can be obtained from a Boltzmann plot as

$$\log(I_n) = \log \frac{F_{ul} \cdot \lambda}{g_u A_{ul}} = B - AE_u, \qquad (4)$$

where F_{lu} is the relative flux of a transition from upper to lower level ($u \to l$), B and A are constants,

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[3] Note here that it is because, in the emission, deexcitation goes as $u \to l$, it is not necessary that the level l has a Boltzmann distribution.

where $A = 1/kT$ is the temperature indicator,[4] then from this value we can estimate the electron temperature from Eq. (4).

If all lines of a series follow the Boltzmann plot, as it is assumed in Eq. (4), from the constant A the electron temperature can be determined, and we can say that for this series the Partial Thermodynamical Equilibrium (PLTE) exists (see van der Mullen et al. 1994, Fujimoto and McWhirter 1990). Note here, that the PLTE condition are not necessarily identical with the pure LTE conditions. The plasma in which PLTE exist for one series can be non-stationary and/or two-temperature plasma (for more details see van der Mullen et al. 1994). Also, in investigation of the BLR physics, very often the Balmer line ratios or Balmer decrements are used. At first glance, the Boltzmann plot looks like the Balmer decrement, but it should be pointed out that it is NOT the same as the Balmer decrement, and the initial assumption in the Boltzmann plot is that the populations of the upper levels in e.g. Balmer series follow the Boltzmann-Saha equation.

In the case of the PLTE, the BP method can be used for the electron temperature diagnosting, and vice versa, if it is possible to apply BP on a line series, it indicates the presence of the PLTE. But, as it was already noted (Popović 2003), an alternative to PLTE in Balmer series of the BLR of some AGN might be intrinsic reddening, and a value of $A > 0.3$ is estimated to be the lower limit for A that can be used in temperature determination. Note here, also, that the accuracy of this method depends on the number of lines available and on the energy interval (ΔE) between excited levels involved, and that it should be $\Delta E > kT$.[5] In the case $\Delta E < kT$, even if the BP works, the determined temperatures are with higher errors. In a prevous paper (Popović 2003) it is estimated that the accuracy of the determined temperature of BLRs by this method lies within the frame of 30%.

On the other hand, one cannot expect the presence of a homogeneous distribution of physical parameters and density of emitters along the line of sight. But, if we still have the population following the Boltzmann-Saha equation, Eq. (1) can be written as:

$$I_{lu} = \frac{hc}{\lambda} g_u A_{ul} \int_0^\ell \frac{N_0(x)}{Z} \exp(-E_u/kT_e(x))dx \quad (5)$$

and if the BLR is divided in small layers with the same physical conditions and emitter density, we can write:

$$I_{lu} = \frac{hc}{\lambda} g_u A_{ul} \sum_{n=1}^{n} \frac{N_0(i)}{Z} \exp(-E_u/kT_e(i))\ell_i. \quad (6)$$

Assuming that the temperatures across the BLR vary as $T_i = T_{av} \pm \Delta T_i$ and the emitter densities as $N_0(i) = N_0^{av} \pm \Delta N_0(i)$, Eq. (6) can be written as:

$$I_{lu} = \frac{hc}{\lambda} g_u A_{ul} \frac{N_0^{av}}{Z} \exp(-E_u/kT_{av})\ell \times \delta(N_0, T) \quad (7)$$

where

$$\delta(N_0, T) = \sum_1^n (1 + \delta N_0(i)) \exp[1/(1 + \delta T_i)] \frac{\ell_i}{\ell}, \quad (8)$$

where $\delta T_i = \Delta T_i/T_{av}$ and $\delta N_0 = \Delta N_0/N_0^{av}$. If in a BLR the temperature and emitter density do not vary very much, i.e. if $\Delta N_0/N_0 << 1$ and $\Delta T_i/T_{av} << 1$, then $\delta(N_0, T) \approx 1$ and the Eq. (4) can be used to determine T_{av} in the BLR.

Note here, that the self-absorption can also affect the Balmer line ratios (see e.g. Netzer 1975), but it seems that the BLR (or, at least, a part of the BLR) is optically thin (e.g. Corbin and Borson 1996, see also the discussion above). Moreover, the majority of broad lines in AGN have no strong asymmetry which should be present if self-absorption were dominant (Ferland et al. 1979); of course it does not automatically mean the absence of Balmer self-absorption (see Ferland et al. 1979), but it can also indicate that most of the observed Hα emission results from collisional excitation (Ferland et al. 1979). It seems that collisional excitation has leading role in formation of the Balmer lines in some BLRs (around 30% of broad line AGN from a SDSS sample show that the Balmer lines follow BP, see La Mura et al. 2006). In this case, the opacity is proportional to the density of atoms in $n = 2$ state and the collisional photon generation rate for the Balmer lines will be distributed fairly uniformly throughout their optical depth, provided that the electron density and temperature do not vary drastically across (one part of) the BLR, where the collisional excitation is dominant. Then one can use the BP method for diagnosing an averaged temperature in the region. Such a scenario was proposed by Ferland et al. (1979) in order to explain the absence of line asymmetry in most of AGN. Moreover, this is consistent with the mentioned ratio of the Lyα and Hα fluxes. Regarding this investigation, one can conclude that the largest part of the emitted photons in the broad Balmer lines (which follow the BP) are collisionally created.

As noted in 2.1, the multicomponent BLR should have various physical properties and in this case one still can conclude about the physics using the BP; for more details see Popović et al. (2006c) and Ilić et al. (2006).

Note here that the BP method (Popović 2003, 2006) does not take into account any 'a priori' given physics in the BLR, besides that Balmer lines originate in the same emitting region. Also, the method includes the intensities of all lines from Balmer series, not only the ratio of some of the lines. Also, it should be noted here that at around of 30% of AGN, the Balmer lines follow the BP (see La Mura et al. 2006).

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[4] if we use $\log_{10}$ in Eq. (2), then $A' = \log_{10}(e)/kT$, and this value will be used in the paper.

[5] For the Balmer series, $\Delta E \approx 1.23$ eV, which corresponds to $T \approx 15000$ K.

3.3 The line profiles: Electron scattering

The line profiles of broad lines emitted from the BLR are mainly affected by kinematics in the BLR. Recently, Laor (2006) showed that, in the low luminous AGN NGC 4395, the line shape can be affected by electron scattering. He used this to develop a method that uses the line profiles to determine the electron density and temperature. The line profile is so-called logarithmic, and fitting the line wings one can obtain the physical parameters in the BLR, assumed to be optically thin (for more details, see Laor 2006). The problem with this method is that many effects can be expected to affect the line profiles (even the gravitational field, see e.g. Popović et al. 1995), and the method can be very useful in the case of lowly luminous AGN, as it was originally applied by Laor (2006).

4. CONCLUSION

In this paper, the geometry and physical properties in the BLR are discussed. The BLR is very close to the massive black hole and is affected by strong radiation from the central part. Various geometries can be considered in the attempts to explain the complex broad line shapes of AGN. Probably, the BLR is complex and may be composed of two or more geometrically different regions. But, according to a standard model, one can expect that an accretion disk emission is present in the BLR. This emission should mainly contribute to the broad line wing shapes. On the other hand, the electron temperature and density should also vary across the BLR, but it seems that, in a number of AGN, the population of the Balmer series follow Saha-Boltzmann equation and one can at least have information about an average temperature in the region. This can be of help in applying more sophisticated methods for calculation of the physical conditions in the BLR.

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ШИРОКОЛИНИЈСКИ РЕГИОН КОД АКТИВНИХ ГАЛАКТИЧКИХ ЈЕЗГАРА: КИНЕМАТИКА И ФИЗИКА

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Прегледни рад по позиву

У раду је дата дискусија о физици и кинематици у широколинијској области код активних галактичких језгара. Разматрају се могући физички услови у овој области и дискутују проблеми везани за одређивање физичких параметара. Такође се разматра могућност да бар један део емисије у широким линијама долази из акреционог диска.