BALMER LINES AS DIAGNOSTICS OF PHYSICAL CONDITIONS IN ACTIVE GALACTIC NUCLEI
BROAD EMISSION LINE REGIONS

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ABSTRACT

Using a well-known method for laboratory plasma diagnostics, the Boltzmann plot, we discuss the physical properties in the broad-line regions (BLRs) of active galactic nuclei (AGNs). We apply the Boltzmann plot method to Balmer lines on a sample of 14 AGNs and find that it may indicate the existence of “case B” recombination or partial local thermodynamical equilibrium (PLTE). For the BLR of AGNs, where PLTE exists, we estimated the electron temperature and density of the BLRs. The estimated electron temperatures ($T \sim 13,000–37,000$ K) are in good agreement with previous estimates. The estimated electron densities depend on the opacity of the emitting plasma in the BLRs. They range from $N_e \sim 10^9$ cm$^{-3}$ for optically thick to $N_e \sim 10^{14}$ cm$^{-3}$ for optically thin emission plasma in the BLRs. The estimated electron temperature has been shown to be velocity-dependent, and it decreases for higher velocities. Although the alternative explanation to PLTE indicated by the Boltzmann plot may be considered (e.g., high intrinsic reddening), the method may give a quick estimate of physical conditions in the BLRs before applying the sophisticated methods.

Subject headings: galaxies: active — galaxies: nuclei — quasars: emission lines

1. INTRODUCTION

The emission-line spectrum of active galactic nuclei (AGNs) is produced over a wide range of distances from the central continuum source and under a wide range of physical and kinematical conditions (see Sulentic et al. 2000 and references therein). The line strengths, their widths, and shapes, are powerful tools for emitting gas diagnostics in different parts of the emitting region of an AGN. The physics in the broad-line region (BLR) is more complicated than in the narrow-line region (NLR). Classical and recent studies point toward photoionization as the main heating source for the BLR emitting gas (see, e.g., Kwan & Krolik 1981; Osterbrock 1989; Baldwin et al. 1995, 1996; Marziani et al. 1996; Ferland et al. 1998; Krolik 1999). The photoionization, recombination, and collisions can be considered as relevant processes in BLRs. At larger ionization parameters recombination is more important, but at higher temperatures the collisional excitation also becomes important, as well as in the case of low-ionization parameters. These two effects, as well as radiative-transfer effects in Balmer lines, should be taken into account to explain the ratios of hydrogen lines (Osterbrock 1989; Krolik 1999).

Different types of the physical conditions and processes can be assumed in order to use the emission lines for diagnostics of emission plasma (Osterbrock 1989; Griem 1997; Ferland et al. 1998). Although “in many aspects the BLRs are physically as closely related to stellar atmospheres as traditional nebula” (Osterbrock 1989), the plasma in the BLR probably does not come close to being in complete LTE. However, there may still be partial local thermodynamical equilibrium (PLTE) in the sense that populations of sufficiently highly excited levels are related to the next ion’s ground-state population by Saha-Boltzmann relations (van der Mullen et al. 1994) or to the total population in all fine-structure levels of the ground-state configuration (see Griem 1968, 1997). The PLTE for different types of plasma—ionizing, recombing plasma, and plasma in ionization balance—were discussed in Fujimoto & McWhirter (1990). They found that the populations of higher lying levels are well described by the Saha-Boltzmann equation. On the other hand, van der Mullen et al. (1994) confirmed that “if electrons realize an equilibrium between ionization and recombination in a two-temperature radiationless plasma, then the Saha equation can be obtained by replacing the thermodynamic temperature by the electron one.” Moreover, recently Popović et al. (2002) found that the Balmer lines of NGC 3516 indicate that the Balmer line emitting region may be in PLTE.

The aim of this paper is to test the existence of PLTE and discuss the possibility of estimation of the relevant physical processes and plasma parameters in BLRs using the Boltzmann plot of Balmer lines.

2. THEORETICAL REMARKS

As a simple case let us consider the optically thin plasma. In the case of plasma of the length $l$ along the line of sight, the spectrally integrated emission-line intensity ($I_{\lambda}$) is given as (see, e.g., Griem 1997; Konjević 1999)

$$I_{\lambda} = \frac{hc}{\lambda} g_u A_u \int_0^l N_u dx \approx \frac{hc}{\lambda} A_u g_u N_0 \frac{N_u}{Z} \exp(-E_u/kT_e),$$

(1)

where $\lambda$ is the transition wavelength, $g_u$ is the statistical weight of the upper level, $A_u$ is the transition probability, $Z$ is the partition function, $N_0$ is the total number density of radiating species, $E_u$ is the energy of the upper level, $T_e$ is the electron temperature, and $h$, $c$, and $k$ are the well-known constants (Planck, speed of light, and Boltzmann constant, respectively).

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If the plasma is in PLTE, the population of the parent energy states adheres to a Boltzmann distribution uniquely characterized by its excitation temperature \( T_e \) in eq. [1]), and this temperature may be obtained from a Boltzmann plot when the transitions within the same spectral series are considered,

\[
\log(I_u) = \log \frac{\lambda}{g_u A_u} = B - AE_u ,
\]

where \( I_u \) is the relative intensity of transition from the upper to the lower level \( (u \rightarrow l) \) and \( B \) and \( A \) are constants, where \( A \) indicates temperature, which we call the temperature parameter.

If we can approximate the \( \log(I_u) \) as a linear decreasing function of \( E_u \), then (1) it indicates that PLTE may exist at least to some extent in the BLR; (2) if PLTE is present, then the population adhering to a Boltzmann distribution is uniquely characterized by its excitation temperature. Then we can estimate the electron temperature from equation (2), \( T_e = 1/(kA) \), where \( k = 8.6171 \times 10^{-5} \text{ eV/K} \) is the Boltzmann constant; (3) if PLTE is present, then we can roughly estimate the minimal electron density in the BLR. Here, we should mention that “case B” recombination of Balmer lines can bring the \( \log(I_u) \) versus \( E_u \) as linear decreasing function (Osterbrock 1989). However, regarding the physical conditions (electron densities and temperatures) in BLRs in this case, the constant \( A \) is too small \( (A < 0.2) \), and the Boltzmann plot cannot be applied for diagnostics of electron temperature even if PLTE exists (see discussion in § 4). Moreover, in this case the Boltzmann plot method can be used as an indicator of case B recombination in BLRs of some AGNs.

Taking into account that the Balmer lines originate from the same series, we can use the Boltzmann plot relation for testing the existence of PLTE or case B recombination. Also, we should mention here that we will assume that \( \ell \), the length of the Balmer line formation region, is the same for all Balmer lines.

3. OBSERVATIONS, DATA REDUCTIONS, AND MEASUREMENTS

In order to test the existence of PLTE in BLRs, we use Hubble Space Telescope (HST) observations obtained with the Space Telescope Imaging Spectrograph (STIS) and Faint Object Spectrograph (FOS), covering the wavelength ranges 2900–5700 Å and 6295–6867 Å (rest wavelength). From the very large database of AGN spectra at HST archive we selected the objects using following selection criteria: (1) the observation covered the Balmer series wavelength region; (2) the observations were performed on the same day; (3) all the lines from the Balmer series can be recognized, and all have relatively well defined shapes; and (4) we considered only low-redshift objects. The list of 14 selected objects is presented in Table 1.

The spectra were reduced by the HST team. We transformed the wavelength scale to zero redshift taking into account the cosmological redshift of the objects (Véron-Cetty & Véron 2000). After that we estimated and subtracted the continuum. The estimated error of 5%–10% due to subtraction of the continuum is included in the cumulative error (see Figs. 1, 2, and 3). The fluxes of the lines were measured by using the DIPSO software. The measured flux ratios of broad Balmer lines are presented in Table 2.

3.1. Satellite and Narrow Lines

To perform a test we subtracted the narrow and satellite lines from Balmer lines. To estimate the contribution of

![Graph](image)

**Fig. 1.**—Decomposition of the Hβ line of WPV 007. The dots represent the observation, and the solid line is the best fit. The Gaussian components are shown at the bottom. The dashed lines at the bottom represent the Fe II template, [O iii], and Hβ narrow lines.
these lines we used a multi-Gaussian analysis. We fitted each line with a sum of Gaussian components using a χ² minimization routine (Figs. 1–3).

To limit the number of free parameters in the fit of the Hβ line we have also set some a priori restrictions on the narrow components and satellite lines (Popović et al. 2001, 2002). First, the three narrow Gaussians representing the two [O iii] λλ4959, 5007 lines and the narrow Hβ component are preconditioned to have the same redshift and full widths proportional to their wavelengths. Second, we have linked the intensity ratio of the two [O iii] lines according to the atomic value (line strength), 1:3.03. Finally, we have included in the fit a shelf of the Fe II template (Korista 1992; Popović et al. 2001, 2002). An example of fitting the Hβ line region of WPV 007 is presented in Figure 1; the dashed lines are subtracted from the Hβ profile.

In the case of Hα, we assume that the [N ii] λλ6548, 6583 and the Hα narrow components have the same redshift and full widths proportional to their wavelengths (Fig. 2, bottom dashed lines). Taking into account that the two [N ii] lines belong to the transition between the same multiplet, we assume that their intensity ratio is 1:2.96 (see, e.g., Wiese et al. 1966).

In the case of an AGN with strong narrow lines we estimated the contribution of [O iii] λ4363 line in Hβ flux using the ratio of (I₄₉₅₉ + I₅₀₀₇)/I₄₃₆₃ lines adopting the value T ∼ 10,000 K (see Table 11.5 in Osterbrock 1989) and low electron density characteristic for NLRs. Where it was possible, we also fitted the Hγ line assuming that the [O iii] λ4363 line can be represented with one Gaussian having the same full width as [O iii] lines proportional to its wavelength (see Fig. 3). The contribution of the [Ne iii] λ3967 line in Hγ has been neglected.

The error bars, presented in Figure 5, are estimated as cumulative errors due to continuum subtraction error (~10%) and error of the line flux measurements. One should note that we approximatively subtracted narrow and satellite lines, but we estimated that the error in this procedure was within the frame of errors presented on the graphs.

Full Table 2

| Name                | F₁₆₅₄/F₁₄₅₉ | F₁₄₅₉/F₁₁₅₇ | F₁₁₅₇/F₁₃₅₇ | F₁₃₅₇/F₁₅₅₉ | F₁₅₅₉/F₁₇₅₉ | F₁₇₅₉/F₁₉₅₉ | F₁₉₅₉/F₂₁₅₉ | F₂₁₅₉/F₂₃₅₉ | F₂₃₅₉/F₂₅₅₉ | F₂₅₅₉/F₂₇₅₉ | F₂₇₅₉/F₂₉₅₉ | F₂₉₅₉/F₃₁₅₉ | F₃₁₅₉/F₃₃₅₉ | F₃₃₅₉/F₃₅₅₉ |
|---------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Ark 564………………..| 3.78 ± 0.53 | 0.35 ± 0.06 | 0.20 ± 0.03 | 0.13 ± 0.02 | 3.13 ± 0.34 E-13 | 0.354 |
| Mrk 493………………..| 2.45 ± 0.16 | 0.40 ± 0.04 | 0.22 ± 0.04 | 0.14 ± 0.01 | 9.63 ± 0.34 E-14 | 0.169 |
| NGC 1566……………….| 3.17 ± 0.48 | 0.53 ± 0.09 | 0.36 ± 0.06 | 0.39 ± 0.15 | 7.29 ± 0.97 E-14 | ... |
| NGC 4151……………….| 3.40 ± 0.32 | 0.41 ± 0.06 | 0.19 ± 0.01 | 0.11 ± 0.02 | 5.57 ± 0.24 E-12 | 0.357 |
| PG 1116+215………….| 2.94 ± 0.74 | 0.48 ± 0.12 | 0.22 ± 0.08 | 0.087 ± 0.015 | 3.43 ± 0.51 E-13 | 0.316 |
| PG 1402+261………….| 2.69 ± 0.33 | 0.51 ± 0.11 | 0.26 ± 0.04 | 0.11 ± 0.02 | 1.61 ± 0.14 E-13 | 0.201 |
| PG 1626+554………….| 2.94 ± 0.42 | 0.48 ± 0.09 | 0.28 ± 0.06 | 0.19 ± 0.02 | 1.77 ± 0.13 E-13 | 0.122 |
| WPV 007………………..| 3.09 ± 0.42 | 0.53 ± 0.08 | 0.21 ± 0.05 | 0.12 ± 0.03 | 9.99 ± 0.63 E-14 | 0.263 |
| NGC 3227……………..| 4.39 ± 0.31 | 0.41 ± 0.03 | 0.24 ± 0.01 | 0.15 ± 0.02 | 4.71 ± 0.13 E-13 | 0.338 |
| 3C 120………………. | 4.47 ± 0.42 | 0.66 ± 0.06 | 0.26 ± 0.04 | 0.13 ± 0.02 | 7.46 ± 0.31 E-13 | 0.335 |
| 3C 390.3……………..| 5.39 ± 0.33 | 0.36 ± 0.05 | 0.11 ± 0.01 | 0.08 ± 0.01 | 2.30 ± 0.11 E-13 | 0.671 |
| 3C 445………………..| 6.91 ± 0.55 | 0.42 ± 0.05 | 0.24 ± 0.04 | 0.15 ± 0.02 | 1.84 ± 0.10 E-13 | 0.499 |
| 3C 273………………..| 3.19 ± 0.32 | 0.41 ± 0.03 | 0.12 ± 0.01 | 0.06 ± 0.01 | 1.54 ± 0.10 E-12 | 0.522 |
| 3C 382………………..| 4.43 ± 0.31 | 0.35 ± 0.02 | 0.043 ± 0.003 | 0.033 ± 0.004 | 5.23 ± 0.25 E-13 | 0.903 |

Note.—The flux ratio of Ark 564 Balmer lines is taken from Crenshaw et al. 2002.
3.2. Reddening

On the other hand, the reddening effect can influence the Balmer line ratio (see, e.g., Crenshaw & Kraemer 2001; Crenshaw et al. 2001, 2002 and references therein) and consequently the temperature parameter obtained by the Boltzmann plot. Here the Galactic reddening was taken into account using the data from NASA’s Extragalactic Database (NED). In order to test the total (Galactic + intrinsic) reddening influence we have considered the case of Ark 564, where the reddening data are given by Crenshaw et al. (2002). We estimated that the reddening effect can contribute to the Boltzmann plot slope around of 30%–40% [in the case of Ark 564 around of 35%, (k,A)/(k,A)_{redd} = 1.35], but this effect cannot qualitatively disturb the straight line as a function in the Boltzmann plot. The reddening effect will always cause temperatures measured by this method to give smaller values if this effect is not taken into account. In the rest of our sample we did not consider the intrinsic reddening effect.

3.3. Velocity Measurements

The data quality required for a comparison of temperature parameter $A$ as a function of velocity is quite high. The data quality is different for different spectra of AGNs. Consequently, for velocity measurements we used only Hα and Hβ lines. To investigate the velocity obtained on FWHM and FWZI as a function of temperature for considered AGNs, we first normalized the clean profiles of these lines to one and converted the wavelength axis to the $X = (\lambda - \lambda_0)/\lambda_0$ scale (see Fig. 4). In order to investigate the random velocity dependence, which is probably related to physical conditions (in this case electron temperature), we measured FWHM and FWZI of an averaged line profile obtained from Hα and Hβ profiles. The differences between FWHM and FWZI of Hα and Hβ were relatively small, except in NGC 1566.

4. RESULTS AND DISCUSSION

In Figures 5, 6, and 7 and in Table 2 we present our results. As one can see from Figures 5 and 6, the Boltzmann plot of the broad Balmer lines indicates the existence of PLTE at least in some parts of BLRs of a significant fraction of the considered AGNs (mainly BLRGs). If we take into account the fact that intrinsic reddening can amplify the constant $A$, we then have three cases: (1) The Boltzmann plot cannot be applied at all (e.g., NGC 1566). (2) If the Boltzmann plot can be applied but the constant is small, $A < 0.3$, then even if the PLTE exists, the ratio of Balmer line fluxes is nearly independent of temperature. This case can rather be treated as (or indicates) recombination. (3) The Boltzmann plot can be applied and $A > 0.3$. In this case we can consider that PLTE exists in the sense that the populations of the higher lying levels ($n \geq 3$) are well described by the Saha-Boltzmann equation, and excited temperature can be replaced by electron temperature.

From the 14 selected AGNs, we can say that in nine AGNs the Boltzmann plot indicates the existence of PLTE ($A > 0.3, T < 40,000$ K) in the BLR, while in the case of four of them (see Table 2 and Fig. 6) the Boltzmann plot indicates case B recombination in the BLR. In the remaining AGN (NGC 1566) the Boltzmann plot cannot be applied (see Fig. 5). Using this method we can determine the electron temperature. In a favorable laboratory situation, the electron temperature, within the method may be determined within 2%–3%; otherwise, normally an uncertainty of about 5%–10% must be expected for laboratory plasma (Konjević 1999). In our case, the determination of the temperatures is very sensitive to the flux measurements. As one can see from Figure 5, uncertainties in the measured flux are higher for weaker lines. Moreover, the intrinsic reddening effect can increase the temperature. Consequently, the uncertainties in the temperature determination in this case are around 30%. Valid criteria for PLTE and PLTE criteria for the application of this spectroscopic method are widely discussed by Fujimoto & McWhirter (1990), Griem (1997), and Konjević (1999). The measured flux ratio of Balmer lines and measured flux of Hβ line and temperature parameter $A$ are given in Table 2. As one can see from Table 2 there is no strong dependence between the $F_{H\alpha}/F_{H\beta}$ ratio and the temperature parameter. On the other hand, one can see from Table 2 and Figures 6a and 6b the temperature difference between radio-quiet (RQ) and radio-loud (RL) objects. Although this follows the fact that RL and RQ AGNs have different distributions in Balmer line widths (e.g., Wills & Browne 1986), temperature differences in RL and RQ AGNs might be a result of selection biases rather than a difference in the radio properties. From Table 2 and Figures 6a and 6b, one can conclude that in the considered sample of RL AGNs, PLTE might exist in BLRs. Here we should mention that an alternative to the PLTE may be a very high intrinsic reddening in this type of AGN. In any case the electron temperatures are in good agreement with some previous estimates (see, e.g., Osterbrock 1989; Sulentic et al. 2000).

To estimate the electron density we will consider two cases: optically thin and optically thick plasma.

For spatially homogeneous and inhomogeneous plasma, as well as in a steady state plasma (applicable to slowly time varying plasma) but optically thin plasma, the method may be used to estimate the lower limit of electron density (Griem 1997), given that $n_e \sim 7 \times 10^{10} z^6 n_{\text{e} - 1/2} (kT_e/E_H)^{1/2}$ cm$^{-3}$, where $z$ is the charge “seen” by the optical electron ($z = 1$ for neutral emitters), $n_e$ is the principal quantum number of the upper level, and $E_H$ is ionization energy of hydrogen. Taking $n_e = 3$ (for the Hα emission in PLTE),
the lower limit of the electron density is of the order of \(10^{13} - 10^{14} \, \text{cm}^{-3}\) (see also the discussion and Fig. 7.4 in Griem 1997).

On the other hand, we cannot consider pure optically thin plasma in BLRs, and one should consider the case of \textit{optically thick plasma} in BLRs. For optically thick plasma, the equation of radiation transfer should be solved simultaneously with the rate equations for the population densities. However, sometimes it is adequate to assume that a reduced transition probability for the spontaneous transition describes the effect of reabsorption of the line. Within this approximation, one can state that in equation (1) effective transition probabilities decrease by a factor \(N_{\text{esc}}\), that is, the mean number of scatterings before escape, which depends of the optical depth (see eq. [12.6] in Osterbrock 1989).

Assuming that for all lines from Balmer spectral series \(N_{\text{esc}}\) is similar, we still can use equation (2), but in this case the value of critical \(N_e\) should be reduced (Osterbrock 1989) \(N_e' = N_e / N_{\text{esc}}\). Considering the critical electron density one may take the values for the \(\text{H}\alpha\) optical depth \([\tau(\text{H}\alpha) \sim 64-4.5 \times 10^4]\) given in Osterbrock (1989). For these optical depths we obtain the values of electron density within the range \(N_e \sim 10^9 - 10^{12} \, \text{cm}^{-3}\). It is in agreement with previous estimates (Osterbrock 1989; Sulentic et al. 2000). However, in some previous works a high electron density has been also suggested (van Groningen 1987; Sivron & Tsuruta 1993; Brotherton et al. 1994). However, for optical thick plasma the estimated electron densities are in agreement with conventionally accepted for BLRs.

On the other hand, it has been shown that the Balmer line ratios are velocity-dependent in AGNs (Stirpe 1990, 1991), and this is probably related both to a range of physical conditions (electron temperature and density) and to the radiative transfer effects. Although we have a relatively small number of observed AGNs for serious statistical analysis, we analyzed the temperature parameter as a function of random velocities at FWHM and FWZI obtained from an averaged profile of \(\text{H}\alpha\) and \(\text{H}\beta\) lines (Fig. 6). As one can see from Figure 6 the temperature parameter \(A\) tends to increase with velocities, especially in the case of velocities measured at FWZI. In this case the function \(A\) versus FWZI has a linear trend. Also, the difference in \(A\) versus FWHM (Fig. 6a) and \(A\) versus FWZI (Fig. 6b) indicates that the BLR is complex and that physical conditions of regions that contribute to the line core and line wings are different. For the AGNs where \(A > 0.3\) and where PLTE may be present, we plot the estimated electron density as a function of velocities measured at FWHM (Fig. 7a) and FWZI (Fig. 7b). As one can see from Figures 7a and 7b, the electron temperature decreases with velocities. The solid lines in Figures 7a...
and 7b present the best fit with a linear function $T_e = c - (d \times V)$, where $V$ is velocity measured at FWHM and FWZI. For constants $c$ and $d$ we obtained $c = 44.0 \pm 4 \times 10^3$ and $d = 1.14 \pm 0.25$ for velocities measured at FWZI and $c = 37.0 \pm 3 \times 10^3$ and $d = 1.87 \pm 0.50$ for velocities measured at FWHM.

5. CONCLUSION

Using the fact that the Balmer lines belong to the same spectral series, we apply the Boltzmann plot method to test the presence of PLTE in BLRs and discuss the relevant physical processes in a sample of 14 AGNs. From our test we can conclude the following:

1. From the 14 selected AGNs, we found that in nine AGNs the Boltzmann plot indicates the existence of PLTE in BLRs, while in the case of four of them the Boltzmann plot indicates case B recombination in the BLR. In the remaining AGN the Boltzmann plot cannot be applied.

2. The estimated BLR electron temperatures using the Boltzmann plot where PLTE exists are in a range $(1.3-3.7) \times 10^4$ K (within 30% accuracy). They are in good agreement with the previous estimations.

Electron densities in the BLR have been considered for optically thin and optically thick plasma, and we found the following:

1. For optically thin plasma, the electron density in the case of PLTE, at least in some parts of the BLR, should be higher than that conventionally accepted for the BLR.

2. For optically thick plasma, the electron density in the case of PLTE is in agreement with that conventionally accepted for the BLR.

On the other hand, the electron temperatures estimated by using the Boltzmann plot tend to be velocity-dependent as a linear decreasing function of random velocities measured at FWHM as well as at FWZI.

Although an alternative of PLTE in some AGNs may be very high intrinsic reddening effect, the Boltzmann plot

![Fig. 6. Parameter A obtained by the Boltzmann plot for all considered AGNs as a function of random velocities measured at (a) FWHM and (b) FWZI. The values $A = 0.2$ and $A = 0.3$ are shown as a solid and a dashed line, respectively.](image)

![Fig. 7. Measured electron temperature using by Boltzmann plot ($A > 0.3$) as a function of velocities measured at (a) FWHM and (b) FWZI.](image)
method may be used for fast insight into physical processes in the BLR of an AGN prior to applying more sophisticated physical models.

For future investigation it is necessary to do the decomposition of complex Balmer lines in order to find the part where this method can be fully applied and investigate the velocity dependence of Balmer line ratios for a large sample of AGNs.

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