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Inconsistencies of the photoionized model for the broad line region in the Seyfert galaxy NGC 7469

L.S. Nazarova[1*], N.G. Bochkarev[2†]

[1] *Eurasian Astronomical Society (EAAS), Universitetskij Pr. 13, Moscow, 119991, Russia*

[2] *Lomonosov Moscow State University, Sternberg Astronomical Institute (SAI), Universitetskij Pr. 13, Moscow, 119991, Russia*

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We present a study of ultraviolet and optical spectra of the active galaxy NGC 7469 taken as part of the International AGN Watch database. We have measured the CIV/Lα, Lα/Hβ and Hα/Hβ line ratios across the line profiles.

The modeling of the observed line ratios have been done with the photoionization code CLOUDY in two variants, with and without taking into account the turbulence in the Broad Line Region (BLR). The comparison of the observed and theoretical emission shows that there are problems with both variants.

The observed line ratios can be accounted for by two systems of clouds without turbulence. One corresponds to the high-ionization line (HIL) zone with an electron density $n_e \approx 10^{9-11}$ cm^{-3}. It is presumably located above the accretion disk. The other system corresponds to the low-ionization line (LIL) zone which is probably the inner part of the accretion disk and which has a high electron density, $n_e \approx 10^{12.5-13}$ cm^{-3}.

Keywords: Galaxies: active; Galaxies: nuclei; Galaxies: individual (NGC 7469); Galaxies: Seyfert; Modeling: broad line region

1 Introduction

The studies of the flux variations of the broad emission lines of active galactic nuclei (AGNs) have established that they respond to changes in the continuum flux. It is widely acknowledged that the Broad Line Region (BLR) is photoionized by an ultraviolet continuum extending in the X-ray range. Early photoionization models of the BLR [1–3] assumed a covering factor $\Omega \approx 4\pi$ and a continuum distribution accounting for the observed strength of the emission lines. However, the first spectrophotometry of the rest frame UV continuum in high-redshift AGNs showed an apparent turn down of the UV spectrum [4]. MacAlpine [5] showed that there was a severe energy budget problem because such a continuum needed $\Omega \approx 4\ \pi \geq 9$ to match the observed HeIIλ4686 equivalent width. Thus, the observed ionizing continuum provided

*Email: lsnazarova@rambler.ru
†Email: boch@sai.msu.ru

Table 1 Log of spectroscopic observations.

File name	JD(2400000+)	Line
57422	2450253.57	Lyα, C IV
57424	2450253.91	Lyα, C IV
57464	2450264.37	Lyα, C IV
57465	2450265.55	Lyα, C IV
28a	2450253.53	Hβ, Hα
29a	2450254.54	Hβ, Hα
51a	2450264.54	Hβ, Hα
52a	2450266.50	Hβ, Hα

an order-of-magnitude fewer ionizing photons than needed. Netzer [6] pointed out that there is a serious energy-budget discrepancy for other lines. Korista et al. [7] suggested that the UV-EUV SED might be double-peaked. This problem has been discussed for NGC 5548 by Dumont et al. [8] and by Gaskell et al. [9]. Dumont et al. [8] favored a non-radiative heating of the BLR as the solution to the energy-balance problem. Gaskell et al. [9] take into account the turbulence in the BLR. Turbulence has a significant effect on the shape and smoothness of AGN line profiles [10, 11]. Lines escape more easily owing to the smaller optical depth (non-dissipative internal turbulence) and turbulence motions also affect line transfer. The spectrum grows stronger as the turbulence increases. The effect is accounted for by the Sobolev's escape-probability method which has been used for interpretating the observed ratios $L\alpha$/Hβ and HeIIλ1640/HeIIλ4686 in AGNs [12–14].

We plan to consider here the energy budget and line variation problems in NGC 7469 taking into account turbulence. The paper is organized as follows. Information about the observational data is given in Section 2. The photoionization models, analysis of the line budget and line variations are given in Section 3. The results of line ratio modeling are discussed in Section 4, and conclusions are given in Section 5.

2 Observational data

The spectra of 3C390.3 were extracted from the AGN Watch database, in the period June 2 to June 30 1996 for optical and in the period June 2 to 29 June 1996 for UV spectra. We chose to work with those taken at the time of the maximum and minimum luminosity (see Table 1).

Table 2 presents the data from [15] and [16]. The fluxes are in units of 10^{-14} erg s^{-1} cm^{-2}.

It is interesting to notice that the variable fraction of the UV lines CIV and Lα (4.24% and 1.16%) is smaller than in the double-peaked galaxy 3C390.3 (84.6% and 47.7% [17]). The variable fraction of the Balmer lines Hβ and Hα (9.65% and 2.9%) is also small compared to 3C390.3 (36.3% and 29.5% [18]).

Table 2 Data on line and continuum fluxes.

Line	Max	Min	Mean flux	Var/Mean (%)
Lα	198.8	195.9	197.3	1.16
CIV	279.4	267.8	273.6	4.24
Hβ	80.33	77.52	78.92	3.5
Hα	393.28	391.1	392.195	0.55
F_ν(1315 Å)	5.67	3.33	4.5	52
CIV/Lα	1.4	1.36	1.38	2.89
Lα/Hβ	2.47	2.52	2.5	8.17
Hα/Hβ	4.89	5.04	4.96	3.02

3 Analysis of the line profiles

The profiles of CIV, Lα, Hβ and Hα have been divided into seven parts, the width of each being equal to 2000 km s^{-1}. The core of the lines is measured between –1000 and +1000 km s^{-1}. Thus the blue and red wings have a width of ±7000 km s^{-1}.

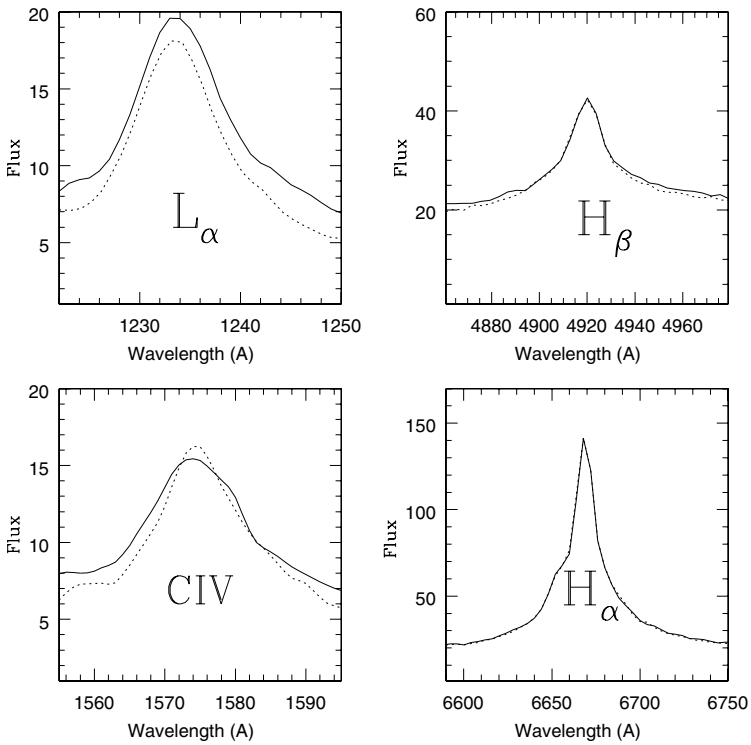


Figure 1 The profiles of the high ionization lines CIV and Lα, and of the low ionization lines Hα and Hβ, for the minimum (dotted line) and maximum (solid line) of the nuclear activity. The fluxes are in units of 10^{-14} erg s^{-1} cm^{-2}.

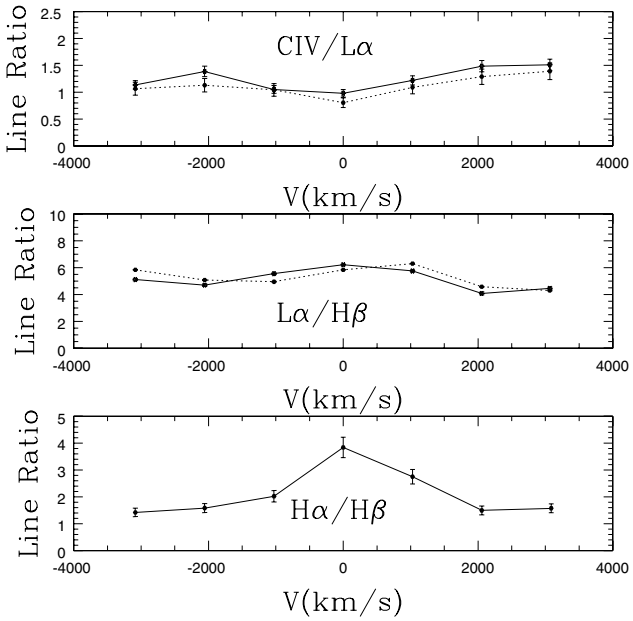


Figure 2 Line ratios CIV/Lα, Lα/Hβ and Hα/Hβ for the maximum (solid line) and for the minimum (dotted line) of the nuclear activity. The line ratios are shown for two periods: 1) close to the minimum – JD2450253.53, 2450254.54 for the Balmer lines and 245253.57, 253253.91 for the UV lines; 2) close to the maximum – JD2450264.54, 2450266.50 for the Balmer lines, and 2450264.37, 2450265.55 for the UV lines.

Figure 1 shows the line profiles of the high (Lα and CIV) and of the low (Hα and Hβ) ionization lines. The profiles of low ionization lines stay almost constant, but the high ionization lines display small differences.

Figure 2 presents the line ratios CIV/Lα, Lα/Hβ and Hα/Hβ as a function of velocity for the minimum and maximum of the nuclear activity.

The CIV/Lα ratio is low in the low-velocity part of the line profile and slightly higher in the blue wing, particularly when NGC 7469 is more active. The Lα/Hβ ratio is high at low velocity and decreases in the wings for both high and low states of the nuclear activity. An opposite velocity dependence is seen in most AGNs [19] in the far wings, where Lα is usually broader than the Balmer lines. The ratio strongly depends on the reddening. It increases the Lα/Hβ ratio along the line profiles but cannot change the width of the lines. When taking into account the reddening, the Lα/Hβ ratio is higher, and the Hα/Hβ ratio should decrease along the line profiles.

4 Photoionization models

The broad line spectrum is computed with so-called "photoionization models". Most popular at present is the photoionization code "CLOUDY" which consists of a shell

of gas (or cloud) in ionization and thermal equilibrium under the action of an external flux of radiation illuminating one face. We have used CLOUDY modern version (c00.08: [20]), in its plane parallel version, and assuming solar abundances. Photoionization models rely on the following input parameters: the flux and gas density, the spectral distribution in the continuum, the column density and the element abundances. The input parameters have been discussed in our previous paper [21]. We only mention the parameters in calculations. The models were calculated with a gas density $n_e = 10^{7-13}$ cm^{-3}. The fluxes in the continuum have been taken in NASA/IPAC Extragalactic Database. The photoionization models were calculated for two states of nucleus activity, which differ at λ 1315 Å by 52%.

The geometrical thickness, h, is assumed to be not larger than 10 light days. When the density is small ($\leq 10^9$ cm^{-3}), we stopped the computation at a column density $\log N_h = 16.4$ cm^{-2} because for a low electron density, a small column density favors the emission of both the high- and low-velocity emission from predominantly optically-thick clouds. We also investigated the effect of significant (1000 km/s) (non-dissipative) internal turbulence.

4.1 The energy–budget problem

Dumont et al. [8] provided evidence of three inconsistencies in NGC 5548: an energy budget problem, a line variation problem and a line ratio problem. The energy budget problem is more prominent for low ionization Balmer lines: the observed lines are more intense than the computed ones. It is thus interesting to study the energy budget in Seyfert galaxy NGC 7469. The calculated line fluxes are F_{cal} and the observational line fluxes are F_{obs}. Despite the fact that we do not know the fluxes emitted by the BLR we can determine the value which corresponds to the maximum emitting surface. This surface is equal to $(\Omega/4\pi)_{max} \cdot 4\pi R^2$, where R is the radius of the BLR and $(\Omega/4\pi)_{max}$ is the maximum coverage factor of the central source by the BLR. The lines are not emitted in equal amount by both sides of the clouds. Due to absorption of $L\alpha$ in the weakly ionized layers of the clouds, $L\alpha$ is emitted exclusively by the illuminated side, if they are optically thick to the Lyman continuum. This is also true for Hα and Hβ lines when the column density is large. It means that the maximum coverage factor of the emission regions of all lines is not unity, but 1/2.

The relation between the computed and observed line fluxes is a function of R^{-2}. Since the time lag for the Hα and Hβ lines could be $\approx$ 5 light days while the high-ionization lines C IV and $L\alpha$ have time lags $\approx$ 2.5 light days [16] the line fluxes F_{cal} have been computed for two different distances from the centre.

The observed luminosity in a line is $L = f_{obs} \cdot 4\pi D$, where the distance of NGC 7469 is $D = 62.7$ Mpc according to NED. The observed flux f_{obs} from Table 2 in the lines at a distance R from the centre is related to F_{obs} by: $F_{obs} = f_{obs} \cdot 4\pi D^2/2\pi R^2$.

The coverage factor used here is $\Omega/4\pi = 1/2$, but it could be significantly less.

The energy–budget problem can be solved if $F_{cal} \geq F_{obs}$. We consider thus the cases $\Delta = F_{cal}/\ F_{obs} \geq 1$.

The relative fluxes $\Delta = F_{cal}/F_{obs}$ computed for two distances from the centre (Fig. 3) shows that Δ is significantly less than unity, and increases with distance. It is an obvious problem for all lines.

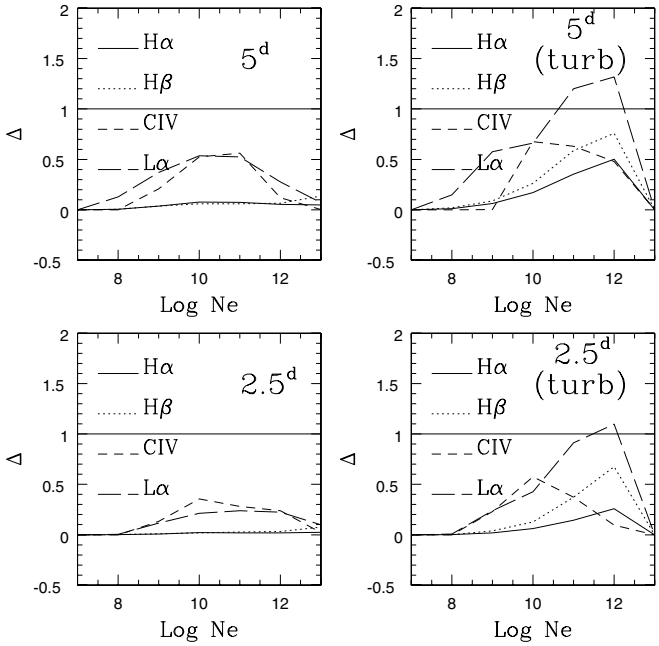


Figure 3 Parameter Δ for emission lines versus the electron density for different lines and for two distances from the center. $\Delta = 1$ is the horizontal solid line.

When we take into account the turbulence (1000 km/s), Δ is still less than unity for the low ionization lines Hα and Hβ. The high ionization line Lα (the case with turbulence) has no energy budget problem at electron densities $\approx 10^{11}$ cm^{-3}.

4.2 The line variation problem

Dumont at al. [8] showed also that the variations of the line fluxes versus the variations of the ionizing flux in NGC 5548 are inconsistent. Since the ionizing flux is not known, it has to be related to the UV flux, more precisely to the flux at 1350 Å. Each line draws its energy from a specific part of the ionizing continuum: Lα and CIV from the continuum near 50 eV, and Balmer lines and other low ionization lines from EUV and soft X-ray continuum.

Dumont et al. [8] estimated that a flux variation by a factor 2 at 1350 Å in NGC 5548 corresponds to only a variation of 50% in the EUV and soft X-ray range. However the EUV flux δF_{EUV} is more variable than the UV flux δF_{1350}, which writes: $\delta F_{EUV}/\delta F_{1350} \geq 1$. Thus it contradicts the observations and implies that a large fraction of the low ionization lines is emitted in a region which has only very weak variations or no variation at all.

Let us consider the line variation problem in NGC 7469. Nandra et al. [22] using RXTE observations found in NGC 7469 a strong spectral variability and suggest that the power-low index is correlated with the level of the EUV and UV continua. Blustin

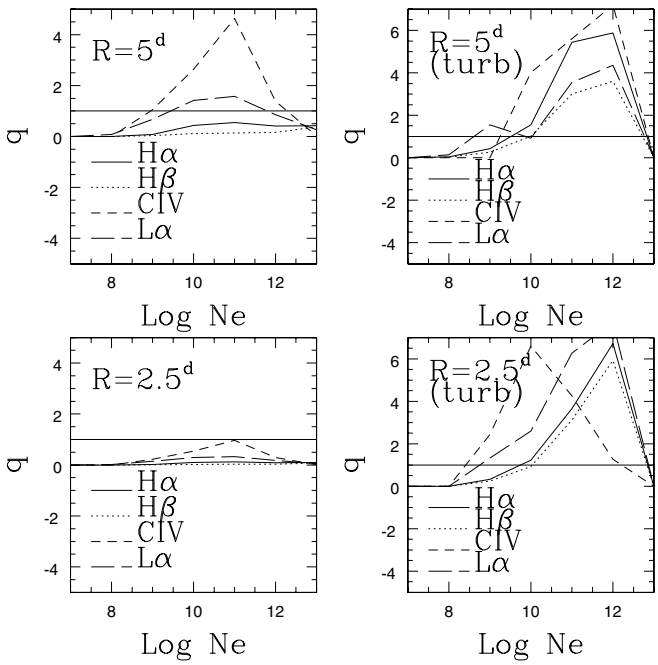


Figure 4 Parameter q versus the electron density for different lines and for two distances from the center. $q = 1$ is the horizontal solid line.

et al. [23] from XMM-Newton observations of NGC 7469 found that the UV shows no significant variability within the 10% error, while the flux in the band 6–10 keV increased by $\approx 20\%$ over the 45 ks observation time whereas the most variable band (0.2–2 keV) increased by 55% in the first 15 ks. In summary X-ray bands show big variations compared to UV data.

The variations of the observed fluxes CIV, Lα, Hα and Hβ were taken from Table 2 as $f_{obs}^{var} = f_{max}^{obs} - f_{min}^{obs}$.

The coverage factor is assumed to be maximum like for the energy balance problem: $\Omega/4\pi = 1/2$. Thus the variations of the fluxes at a distance R from the centre F_{obs} can be expressed as $F_{obs} = f_{obs}^{var} \cdot 4\pi D^2/2\pi R^2$.

The theoretical line fluxes for NGC 7469 were calculated with the ionizing continuum in NGC 7469 (taken from NASA/IPAC Extragalactic Database) which is assumed to vary proportionally to the flux at 1350 Å between the minimum f_{min}^{cal} and the maximum f_{max}^{cal} (Table 2). The difference of the line fluxes, $F_{var}^{cal} = f_{max}^{cal} - f_{min}^{cal}$ were computed for the two distances from the centre 2.5 and 5 light days. The line-variation problem would not arise if the variation of the calculated line fluxes is equal to or less than the variations of the observed line fluxes: $q = F_{cal}^{var}/F_{obs}^{var} \leq 1$.

Figure 4 shows the results without turbulence (left side): $q \leq 1$ for the low ionization lines at both distances, whatever the density is. When taking into account turbulence, the calculations (right side) shows that $q \geq 1$ for an electron density larger than 10^{10} cm^{-3}. Thus, the line-variation problem does not exist in NGC 7469 for low

ionization lines if there is no turbulence. However the energy-budget problem still exists for low ionization lines with and without the turbulence.

5 Modeling of the line ratios

Figure 5 shows the computed line ratios of CIV/Lα, Lα/Hβ and Hα/Hβ for the two cases: without (left side) and with turbulence (right side), at two distances from the center: 5 light days (solid line) and 2.5 light days (dotted line) for the maximum nucleus activity (Fig. 5). The comparison of the observed (Fig. 2) and computed (Fig. 5) CIV/Lα, Lα/Hβ and Hα/Hβ line ratios gives an information about the electron density along the line profiles.

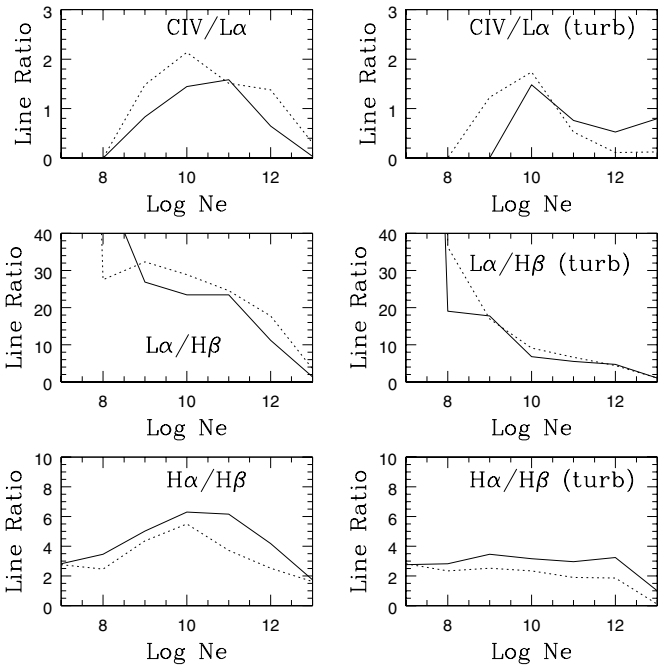


Figure 5 CIV/Lα, Lα/Hβ and Hα/Hβ line ratios versus electron density computed at distances from the center: 5 (solid line) and 2.5 (dotted line) light days, for the maximum of nucleus activity.

The observed line ratios: CIV/Lα, Lα/Hβ and Hα/Hβ vary along the line profiles. The CIV/Lα ratio is $\approx$ 0.8–1 at the line centre, and $\approx$ 1.2–1.5 in the line wings, at minimum and at maximum. According to the theoretical line ratios (Fig. 5, left side) the observed CIV/Lα line ratio could be explained if:

a) the density is $10^{8.5-9.5}$ cm^{-3} at the line center and increases to 10^{11} cm^{-3} in the wings.

b) the density is 10^{10-11} cm^{-3} in the wings and increases to 10^{12-13} cm^{-3} at the line center.

Note that the contribution of the low-density gas from NLR was not removed because of the poor wavelength resolution of the IUE satellite's observations.

Figure 2 shows that at the minimum and maximum, the Lα/Hβ and Hα/Hβ ratios are high at low velocities and decrease at high velocities. However, we did not correct for reddening. It would not change the CIV/Lα ratio much but the Lα/Hβ and Hα/Hβ ratios are strongly reddening dependent, and this must be taken into account in our analysis. The Galactic Extinction E(B-V)= 0.069 (NED) changes the line ratios significantly: Lα/Hβ increases to 7.86 in the centre and Hα/Hβ decreases to 3.0 in the centre.

Thus, according to the theoretical line ratios obtained without taking into account turbulence (Fig. 5, left side), the observed Lα/Hβ ratio could be explained as due to a medium with a density $10^{12.5-13}$ cm^{-3}. The Hα/Hβ ratio shows that the electron density could be very high $\geq 10^{13}$ cm^{-3}. Such high electron density at a distance 2–5 light days from the centre of galaxy corresponds to the accretion disk. However the high ionization lines are well accounted for by a low density gas $10^{8.5-11}$ cm^{-3}, located above an accretion disk.

The theoretical line ratios taking into account the turbulence (1000 km/s) are presented in Fig. 5 (right side). These line ratios are significantly low. According to Fig. 5 (right side) the CIV/Lα line ratio could explain electron density $\approx 10^{10}$ cm^{-3}. The observed Lα/Hβ and Hα/Hβ line ratios could explain electron density $\approx 10^{11-12}$ cm^{-3} and $\approx 10^{11-13}$ cm^{-3} respectively.

When the turbulence is taken into account, the electron density is 10 times smaller for the same value of the line ratios.

6 Conclusions

We present a study of UV and optical spectra of the active galaxy NGC 7469 taken as part of the International AGN Watch database. We have measured the CIV/Lα, Lα/Hβ and Hα/Hβ ratios at different velocities across the line profiles.

The CIV/Lα ratio at minimum and at maximum is $\approx$ 0.8–1 at the line centre and $\approx$1.2–1.5 in the line wings.

The Lα/Hβ and Hα/Hβ ratios at minimum and maximum are high at low velocities and decrease at larger velocities. Lα/Hβ (taking into account the Galaxy extinction) is to 7.86 at the centre and 5.9 in the wings, and Hα/Hβ is to 3.0 at the centre and 1.3 in the wings.

Modeling the observed broad lines of NGC 7469 using the photoionization code CLOUDY leads to the following conclusions.

The observed line ratios can be accounted for by two systems of clouds. One system corresponds to the high ionization line (HIL) zone having an electron density $n_e \approx 10^{9-11}$ cm^{-3}. It is presumably located above the accretion disk. The other system corresponds to the low-ionization line (LIL) zone with a high electron density from $n_e \approx 10^{12.5}$ up to $\geq 10^{13}$ cm^{-3}.

The modeling of the observed line ratios in the Broad Line Region (BLR) shows that the line-variation problem does not exist in NGC 7469 for low ionization lines if there is no turbulence. However, the energy-budget problem still exists for low ionization lines with and without the turbulence.

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