Probing broad-line region of the weak line quasar
SDSS J094533.99+100950.1

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Abstract.
SDSS J094533.99+100950.1 is a weak line quasar (WLQ) characterised by a low equivalent widths of the high-ionization emission lines such as CIV or HeII, typical iron emission, radio quiescence and X-ray weakness. In our work we tried to answer the question if it is possible that observed emission is intrinsically weak and come from not fully developed broad emission-line region (BELR). We also analyse the observed continuum to check if it is able to ionize a BELR gas and reproduce a weakness of emission-lines or this spectral feature can be simply explained by an intrinsic absorption. Our conclusion is that the minimal active galactic nuclei (AGN) engine consisting of an unobscured accretion disk with a partially ionized gas just expanding from the disk atmosphere is enough to explain observed features of SDSS J094533.99+100950.1.

1. Introduction
SDSS J094533.99+100950.1 (thereafter SDSS J0945+1009) is an exceptional quasar at redshift $z \simeq 1.67$ discovered by the Sloan Digital Sky Survey (SDSS) project. Its extremely weak medium-ionization ([CIII], [AlIII]), high-ionization lines (CIV, HeII) together with typical FeII emission and near-ultraviolet power-law continuum are remarkable and puzzling. We present its spectra compared to ordinary quasar composite in Figure 1.

For PHL1811 analogues it was proposed that soft continuum is caused by shielding gas and consequences of soft continuum are low line intensities ([1], [2]). This explanation could be valid for all WLQs. In the case of SDSS J0945+1009 we checked if all observed components can be explained by a rather minimalistic AGN engine — accretion disk around black hole plus single cloud BLR without additional components.

2. Global parameters of SDSS J0945+1009
In Figure 2 we plot photometric points together with the mean spectral energy distribution (SED) of an ordinary quasar composed by [3]. The photometric points span the near-infrared (NIR), optical, and ultraviolet (UV) ranges and comes from the Two Micron All Sky Survey (2MASS) [4], SDSS [5] and the Galaxy Evolution Explorer (GALEX) [6] observational surveys. The Figure 2 shows that the optical-UV continuum of the quasar is soft, steep in UV region and dominated by quasar’s accretion disk. The latest estimation of the black hole (BH) mass equals to $M = 2.9^{+3.5}_{-1.5} \times 10^9 M_\odot$ based on MgII line width and continuum luminosity measured
2.1. Accretion disk continuum

[9] have fitted an accretion disk continuum, where the disk’s matter falls onto a spinning black hole, and they put constraints on parameters of the disk. The fitted parameters were the supermassive black hole mass, $M$, the Eddington accretion rate, $\dot{m}$, the dimensionless spin, $a$, at wavelength 3000Å (see formulas in [7]). This value gives the non super-Eddington accretion rate $\dot{m} = 0.17$. 

Figure 1. Spectrum of SDSS J0945+1009 (red) together with fitted continuum (blue) and iron emission (green). For comparison purposes ordinary quasar composite spectrum come from [8] is plotted in black.

Figure 2. Photometric points of SDSS J094533.99+100950.1 together with ordinary quasar SED taken from [3]. Triangles show 2MASS IR photometric points, squares – optical points observed by SDSS, and hexagons are points which come from GALEX.
and the angle between the normal to the accretion disk and a direction to the observer i.e. the inclination \( i \). The best fit parameters obtained by [9] are \( M = 3 \times 10^9 M_\odot, \dot{m} = 0.14^{+0.11}_{-0.02}, a = 0.3^{+0.1}_{-0.0}, \) and \( \cos i > 0.7 \). In work [10] authors fit SED of SDSS J0945+1009 by the cold accretion disk. They conclude that SED of this object can be produced by the cold disk and a relative low temperature of the disk can explain WLQ spectral features i.e. weakness of emission-lines.

3. Photoionization simulations

The aim of our project is to reconstruct the weakness of the emission-lines in WLQ by modification of its broad emission-line region parameters. We used Cloudy code ([11]) to perform photoionization-based fitting of the BELR assuming that the BELR is represented by a single cloud of plasma. The quasar’s SED can be described by the standard Cloudy AGN two component spectrum:

\[
f_\nu = A \nu^{\alpha_{UV}} \exp(-\frac{h \nu}{k T_{\text{max}}}) \exp(-\frac{h \nu}{k T_{\text{min}}}) + B \nu^{\alpha_x}
\]

where the spectral index \( \alpha_{UV} = 0.7 \), the minimal and maximal effective cutoff temperatures \( T_{\text{min}} = 1.6 \times 10^2 \text{ K} \) and \( T_{\text{max}} = 4 \times 10^5 \text{ K} \), respectively, fit very well the observed continuum. The second part of formula (1) illustrate the behaviour of the spectrum in the X-ray band. SDSS J0945+1009 has been unobserved by Chandra and ROSAT satellite ([12, 13]). Thus, we assume \( \alpha_x = -1 \) and calculate the constant \( B \) from adopting a mean for WLQs \( \alpha_{ox} = -1.7 \). The free parameters are (1) the local hydrogen density, \( n_H \), (2) the radius of the BELR from the central black hole, \( r \), and (3) the hydrogen column density, \( N_H \). We assume the solar abundance.

3.1. Single cloud BELR model

We see in Figure 3 that all line luminosity ratios agree well in a narrow parameter range (intersection of solid lines at \( \log(n_H[\text{cm}^{-3}]) \approx 11, \log(r[\text{cm}]) \approx 18 \)). The narrow intersection region can suggest that all emission lines can be produced in the single cloud or compact set of clouds with narrow range of densities. Absolute line luminosities agree quite well except one line (HeII, which could be underestimated). Additionally, MgII could be overestimated due to blended FeII emission under MgII line. Intersection position depends very weakly on the hydrogen column density (see panels b-e in Figure 3).

3.2. Location of the BELR

It results from our simulation of a single cloud model that the distance of the BELR from BH is approximately \( 10^{18} \text{ cm} \). This preferred location agrees very well with the value \( \log(R_{\text{BLR}}(L_{\text{3000}\AA})[\text{cm}]) = 17.98 \) calculated with use of formula from [14] which is based on the reverberation mapping method.

3.3. Comparison to disk vertical structure

We try to locate the BELR in SDSS J0945+1009 in an environment of the supermassive BH. We independently carry out the next simulation based on the code described by [15] where the disk vertical structure (i.e. relatively cold disk and hot atmosphere) is calculated. Obtained parameters of the disk atmosphere (see Figure 4) are in agreement with those preferred by Cloudy’s simulation — \( \log(n_H[\text{cm}^{-3}]) \approx 11, \log(r[\text{cm}]) \approx 18 \). This supports hypothesis in which the BELR is compact and not fully developed. It appears as an extension of the accretion disk atmosphere.
Figure 3. The observed line intensity ratios in the radius–local hydrogen density plane for the fixed column density: \( N_H = 10^{23} \text{ cm}^{-2} \) (panel a), \( N_H = 10^{21}, 10^{22}, 10^{24}, \) and \( 10^{25} \text{ cm}^{-2} \) (panels b-e, respectively).

3.4. Locally Optimally Emitting Clouds

We also perform calculation of lines luminosities in the Locally Optimally Emitting Clouds (LOC) model where the BELR consists of many clouds. Therefore, each line luminosity is the integral of an emission line flux of a single cloud, \( F(r, n_H) \), over a whole parametric space:

\[
L_{\text{line}} \propto \int \int r^2 F(r, n_H) r^\gamma n_H^\beta \, dn_H \, dr.
\]  

(2)
Figure 4. The local hydrogen density along radius. \( n_H \) has been calculated in the grey disk atmosphere at the effective optical depth = 2/3. Obtained results come from the disk vertical structure simulation ([15]).

Dependence of emitted lines and their observed ratios on \( \beta \) and \( \gamma \) indices are shown in Figure 5. We were able to match observed line luminosities with calculated in LOC model. However, it demands \( \gamma \) and \( \beta \) to be more extreme than those adopted e.g. by [16]. Still line luminosity in this approach depends on the integrating range. LOC method introduces few additional free parameters thus there is many possibilities here which we do not fully explored.
4. Summary
We show preliminary results of photoionization simulations that supports compact BELR scenario in SDSS J0945+1009. The obtained preferred position of the BELR is consistent with the value which comes from the reverberation mapping formula. Additionally, this distance and the calculated local hydrogen density agree with values derived from the disk vertical structure simulations. Those remarks may encourage hypothesis that the BELR in SDSS J0945+1009 is in an early developing stage during active galaxy nuclei activation phase. This scenario is very incentive to explore this possibility. To further investigation it is necessary to answer the question how sensitive results are on simulation setup and on potential inaccuracies in line fitting.

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