The disk emission in the Broad Line Region of Active Galactic Nuclei

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Abstract. We studied the disk emission component hidden in the single-peaked broad emission lines (BELs) of active galactic nuclei (AGN) using a two-component model. We assumed that the broad lines are formed in an accretion disk plus a surrounding non-disk region, with isotropic cloud velocities. To compare simulated line profiles with observed ones we measured the full widths (at 10 per cent, 20 per cent and 30 per cent of the maximum intensity). We found that the hidden disk emission may be present in BELs even if the characteristic of two-peaked-line profiles is absent. We found that in the case of the hidden disk emission in single-peaked broad-line profiles, the disk inclination tends to be small and that the contribution of the disk emission to the total flux should be smaller than the contribution of the surrounding region.

1. Introduction
The detailed structure of the innermost part of Active Galactic Nuclei (AGN) is still an open question. Broad Emission Lines (BELs) are often used for sounding the inermost part of AGN. They show high diversity in their shapes and widths what indicates different kinematical properties of emitting gas. It is widely accepted that the central engine consists of a supermassive black hole fueled by an accretion disk. Using BEL shapes, one can constrain the geometry of the material in the Broad Line Region (BLR) [1]. In some rare cases, where the accretion disk clearly contributes to the BELs, we can investigate the disk properties using broad, double-peaked, low-ionization lines [2, 3, 4, 5, 6]. The rotation of the material in the disk results in one blueshifted and one redshifted peak, while the gravitational redshift produces a displacement of the center of the line and a distortion of the line profile. In some cases, BELs show shoulder-like profiles in the wings, which could indicate that some part of the flux in BELs originate in the accretion disk emission [7, 5, 8].

To explain the complex morphology of the observed BEL shapes, different geometrical models have been discussed [9]. In some cases the BEL profiles can be explained only if two or more kinematically different emission regions are considered [10, 11, 12, 13, 7, 14, 20, 15, 16, 17, 18, 19]. In particular, the existence of a Very Broad Line Region (VLBR) with random velocities at 5000-6000 km/s within an Intermediate Line Region (ILR) has also been considered to explain the observed BEL profiles [9, 17, 18, 19, 21]. Even though, the majority of AGN with BELs
have only single peaked lines, it does not necessarily indicate that the contribution of the disk emission to the BELs profiles is negligible.

Here we give a short overview of our investigation about possibility of a presence of a disk emission flux in AGN emission lines.

2. Data sets and reductions
First sample of 14 AGN spectra was observed with the 2.5 m Isaac Newton Telescope (INT) on La Palma at 2002 [14]. Objects were chosen due to indication of the disk emission in the X-ray part of the spectrum. For some lines with low S/N ratio we used Hubble Space Telescope (HST) observations obtained with the Space Telescope Imaging Spectrograph (STIS) on January 2000 (NGC 3516). Details about observation and data reduction can be found in [20, 14]. The narrow and satellite lines were cleaned [13, 7]. The broad profiles from this sample were fitted with two component model [20].

Second sample contains 90 broad-line-emitting AGN [22], which have been collected from the third data release of Sloan Digital Sky Survey (SDSS)\(^1\). The spectra were already corrected for sky-emission, telluric absorption, the Galactic extinction and redshift [22]. Since the interest was to investigate the broad emission line profiles, we subtracted the narrow components of H\(_{\alpha}\) and the satellite [NII] lines. The spectral reduction (including subtraction of stellar component) and the way to obtain the broad line profiles are explained in more details in [22].

Previously cleaned broad H\(_{\alpha}\) profile was normalized, converted from wavelength to velocity scale, and smoothed using DIPSO software package\(^2\).

The sample of 90 AGN contained the spectra with different FWHM of broad H\(_{\alpha}\) from about 1000 km/s to 7000 km/s, with at least several representatives in every 500 km/s [22].

3. The Model
We assumed that the BELs can be described with two kinematically different components, one contributing to the wings (that we assumed to be emmitted from the disk) and other to the core (emitting clouds that surround the disk with isotropic distribution of the velocities).

The local broadening (\(\sigma\)) and shift (\(z_\lambda\)) of each disk element have been taken into account as in [2], i.e. the \(\delta\) function has been replaced by a Gaussian function:

\[
d\rightarrow \exp\left(\frac{(\lambda - \lambda_0 - z_\lambda)^2}{2\sigma^2}\right),
\]

(1)

We express the disk dimension in gravitational radii (\(R_g = GM/c^2\), \(G\) being the gravitational constant, \(M\) the mass of the central black hole, and \(c\) the velocity of light).

We assumed that the additional emission region can be described by a surrounding region with an isotropic velocity distribution, i.e. the emission line profile generated by this region can be described by a Gaussian function with broadening \(w_s\) and shift \(z_s\). Finally, line profile can be described by the relation:

\[
I(\lambda) = I_d(\lambda) + I_s(\lambda),
\]

(2)

where \(I_d(\lambda)\), and \(I_s(\lambda)\) are the emissions of the relativistic accretion disk and the non-disk region, respectively.

The synthetic profiles generated with this model can fit the line profiles of BELs in AGN, but it is hard to determine the exact physical properties with so many free parameters in the model [14]. First of all, the disk model includes many parameters (the size of the emitting region, the

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1 http://www.sdss.org/dr3
2 http://www.starlink.rl.ac.uk
emissivity and inclination of the disk, the velocity dispersion of the emitters in the disk, etc.). In order to perform numerical tests, one needs to introduce some constraints and approximations:

i) The disk inclination affects the emission obtained from the disk. The observed flux from the disk \( F_d \) is proportional to the disk surface \( S_d \), as

\[
F_d \sim S_{\text{eff}} \sim S_d \cdot \cos(i),
\]

where \( i \) is the inclination, and \( S_{\text{eff}} \) is the effective disk emitting surface, therefore, one cannot expect a high contribution of the disk emission to the total line profile for a near edge-on projected disk.

ii) One should not expect emission of the low ionized lines in the part of the disk too close to the central black hole. Consequently, the model given by [2] can be properly used, i.e. it is not necessary to include a full relativistic calculation [24].

iii) The emissivity of the disk as a function of radius, \( r \), is given by \( \epsilon = \epsilon_0 r^{-p} \), but we fixed the value of emissivity index to \( p = 3 \), since while varying this parameter there were no significant difference between normalized profiles.

iv) Previous estimations of the double-peaked AGN emission lines [2, 3, 4, 5, 25] show that the typical dimensions of an accretion disk that emits low ionization lines are of the order of several thousands \( R_g \). For that reason we did not consider dimensions on the disk larger than 100000 \( R_g \). This was an important approximation to limit the computing time.

v) We consider a systemic velocity shift of the non-disk region (not greater than \( \pm 3000 \) km/s) to test the possibility of the outflow/inflow.

We considered the following parameters to study the simulated and observed BELs profiles:

i) The flux ratio between the non-disk region \( F_s \) and the disk \( F_d \): \( Q = \frac{F_s}{F_d} \) (4)

where \( F_{\text{tot}} = F_s + F_d = (1 + Q)F_d \).

Using this parameter, the total line profile (normalized to the disk flux)\(^3\) can be written as:

\[
\frac{I_{\text{tot}}(\lambda)}{F_d} = \frac{I_d(\lambda)}{F_d} + Q \frac{I_s(\lambda)}{F_s},
\]

where \( I(\lambda) \) is the wavelength dependent intensity. The composite profile is normalized according to:

\[
\mathcal{I}(\lambda) = \frac{I_{\text{tot}}(\lambda)}{I^\text{max}_{\text{tot}}},
\]

where \( I^\text{max}_{\text{tot}} \) is the maximum intensity of the composite line profile.

ii) For the composite line profile \( \mathcal{I}(\lambda) \) we measured full widths at 10%, 20%, 30% and 50% of the maximum intensity, i.e. \( w_{10\%}, w_{20\%}, w_{30\%} \) and \( w_{50\%} \). Then we define coefficients \( k_i \) \((i = 10, 20, 30)\) as \( k_{10} = w_{10\%}/w_{50\%}, k_{20} = w_{20\%}/w_{50\%} \) and \( k_{30} = w_{30\%}/w_{50\%} \) where \( w_{50\%} \) is Full Width at Half Maximum (FWHM). It is obvious that the coefficients \( k_i \) are functions of the radius \( R \) and other parameters of the disk. Using these normalized widths we can compare results for AGN with different random velocities.

iii) We also measured the asymmetry \( (A_i) \) at \( i = 10\%, 20\%, 30\% \) of maximum intensity of the modeled and observed lines as:

\[^3\] This is taken from technical reasons to simulate different contributions of the disk and the non-disk component. First we normalized both line profiles to their fluxes, and after that we rescaled the non-disk component by multiplying it with \( Q \), so the whole profile is given in units of the disk flux.
\[ A_i = \frac{W_i^R - W_i^B}{FWHM}, \]  

where \( W_i^R \) and \( W_i^B \) are red and blue half widths at \( i = 10\%, 20\% \) and \( 30\% \) of the maximum intensity, respectively.

We simulated only the disk profiles, taking into account different values of the disk parameters. In the first instance, the relative importance of the disk contribution to the core or to the wings depends on the disk inclination. The contribution of the disk to the center of the line or to the wings is not so much sensitive to the outer radius, but significantly depends on the disk inclination. A face-on disk contributes more to the core of the line, while a moderately inclined disk (\( 40^\circ > i > 20^\circ \)) contributes significantly to the line wings. For \( i > 40^\circ \) the disk emission will strongly affect the far wings of the composite profile. Another very important parameter is the flux ratio between components, \( Q \).

We found that the presence of the disk emission is difficult to detect in the line profile when the contribution of the disk is smaller than 30\% of the total line emission (\( Q > 2 \)): in the case of a low inclination both the disk and non-disk region contributes to the line core and it is very hard to separate the disk and non-disk region. In the case of a highly inclined disk, the disk emission spreads in the far wings, and could not be resolved from the continuum, especially if the observed spectrum is noisy. For the case of dominant disk emission (\( Q < 0.3 \)), if the inclination is low, the line will be shifted to the red, and if the inclination is high, two peaks or at least shoulders should appear in the composite line profile (see Fig. 1). Consequently, further in the paper we will consider only cases where \( 0.3 < Q < 2 \) [18].

![Simulated line profiles](image)

**Figure 1.** Simulated line profiles emitted by the two-component model for five different inclinations (\( i = 1, 10, 20, 40 \) and 60 degrees, from the narrowest to the broadest line, respectively) for different contributions of the disk to the composite line profiles (denoted by \( Q \) in figures). The inner radius of the disk is taken to be 400 Rg, while the outer radius is 1200 Rg.

We set some constrains in the parameter space, and we constructed a grid of simulated line profiles. As a rough approximation, we fixed the width of the central Gaussian component to the 1000 km/s, as mean value obtained from the two component model fit [20]. As it was shown
in [14], the random velocities in the disk and in the non-disk region were approximately the same, so they were also fixed to the value of 1000 km/s.

For the first sample, the inner radius of the disk was chosen to be $R_{\text{inn}} = 400 \, R_g$, as the mean value of this parameter in the previous fittings [23]. For the outer radius, the chosen value was $R_{\text{out}} = 3000 \, R_g$ [20], since the variation of this parameter, after values of several thousand gravitational radii, did not show significant influence to the shape of the line (especially if the line was noisy).

4. Results

In order to detect possible accretion disk emission in the flux of the single peaked broad emission lines of AGN, we applied several methods (fitting with the model, comparing the measured coefficients with the grid of simulated spectra by this model, and with the model constructed of two isotropic regions that could be represented only with Gaussians: very broad line region (VBLR) and intermediate broad line region (ILR), Gaussian fitting with three components...).

From the Gaussian analysis we could conclude that two distinct kinematic regions might be present in the BELs. The central Gaussian component indicated the existence of the emission from the region with intermediate velocities (ILR), while in the wings two shifted broad Gaussians indicated possible presence of disk-like emission (VBLR). The results for the widths of the emission lines of Fe II template showed that these lines probably originate in the ILR.

From fitting with the twocomponent model we found [19]:

- two-component model can fit well the profiles of broad emission lines from our samples, but it is very hard to determine the disk parameters, because of the large number of the free parameters,
- random isotropic velocities in the surrounding region are similar to random velocities in the disk, what implies that these two regions could be connected through some process (for example through the wind from the accretion disk),
- the values of the parameters indicate that the inclinations are smaller than 50°, and the dimensions of the disk could be from several hundred $R_g$ for the inner radius, to several hundred thousands $R_g$ for the outer radius.

After comparing the measurements of $k_i$ for the sample, with the measurements of the simulated profiles, we could derive the estimates for $i$ and $Q$. As the result, we found that the most of the measured points were between $0.5 < Q < 1.5$, and $10^\circ < i < 25^\circ$ (see Figs. 2 and 3). The results showed a consistence between estimations of $i$ and $Q$ for both H$\alpha$ and H$\beta$, with very small discrepancies [23].

After this analysis, we tested this method to the larger sample of 90 AGN [18]. The measurements were performed in the same way as for 14 AGN, with a difference that we compared them to simulated spectra for the disk dimensions of $R_{\text{inn}} = 600 R_g$ and $R_{\text{out}} = 4000 R_g$ (averaged disk size obtained from the fitting of the double-peaked lines in the paper of [5]). For this sample we measured widths for H$\alpha$ lines. After measuring we noticed that for higher inclinations $i > 30^\circ$ error bars were rapidly increasing (see Fig. 4), and we excluded those few measurements from further analysis. This could indicate that the model may not be suitable for higher inclinations, and that this may indicate significant torus influence. As it could be seen in Fig. 3, most of the measurements are located within $1 < Q < 2$, and $10^\circ < i < 25^\circ$ [18].

5. Conclusions

This investigation indicates the disk emission presence in the flux of single peaked BELs.
Figure 2. The measured width ratios (crosses for the Hα of the larger sample, + and asterisk signs for the Hα and Hβ of the smaller sample, respectively) and simulated values with two component model (solid isolines represent inclinations $i = 10, 15, 20, 25$ and $30$ degrees, respectively and dashed isolines different flux ratios $Q=0.3, 0.5, 0.7, 1, 1.5$ and $2$) for the inner disk radius of $600 \text{ Rg}$ and outer $4000 \text{ Rg}$.

Figure 3. Histograms of the inclination (left) and $Q = F_s/F_{\text{disk}}$ (right) for the sample in the case with (dashed line) and without (solid line) systematic blue shift of the non-disk component. The cases where discrepancies of the inclination estimation were larger than one degree, were not taken into account.

We carried out the following analyzes: i) fitting of single peaked BELs with Gaussians and with two-component model, and ii) comparing line parameters of a sample with simulated profiles.

From our investigations we can conclude that there could be a high probability that the disk emission flux might be present in the single peaked emission line profiles, but with the disk inclinations mainly smaller than $i < 25^\circ$. Such small inclinations and large discrepancies from simulated profiles for higher inclinations should be discussed in the context of unified model, i.e. possible disk orientation to the torus or partial obscuration by the torus (see Fig. 5).

Both of the values ($i > 25^\circ$ and $Q > 1$) may indicate that we have a low inclined disk which contribution to the total line flux is smaller than the non-disk emitting region.
Figure 4. Disk inclination vs. full width at 10 % of line intensity normalized to FWHM ($k_{10}$). The points where discrepancies were more than one degree (mainly above the other points) are denoted with full triangles.

Figure 5. Obscuration of the disk emission: 1) torus, 2) absorbing material around the torus and 3) the region without absorption.

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