Mem. S.A.It. Suppl. Vol. 15, 44

Memorie della
Supplementi

Spectral line shapes as a tool for investigation of kinematics and physics of plasma in quasars

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Abstract. One of the characteristics of quasars is the presence of strong emission lines in their spectra. There are broad and narrow lines indicating broad and narrow line emitting regions (BLR and NLR, respectively). Beside these two regions, a very broad Fe Kα line is often present in the X-ray spectral band. Additionally, in the UV spectral band, the broad absorption line components are present in a fraction of 10% of quasars. Here we give a short overview of investigation of line shapes and their use to diagnose the plasma physics and kinematics in quasar emitting regions.

Key words. Galaxies: active, nucleus; Quasars: spectral lines

1. Introduction

Active Galactic Nuclei – AGN are powerful sources of radiation in a wide spectral range: from γ rays to radio waves. Their extraordinary luminosities (sometimes more than 10.000 times higher than luminosities of "ordinary" galaxies) arise from energy release during accretion, i.e. when orbiting matter in accretion disk, due to lost of its angular momentum, falls into a central supermassive black hole (see e.g. Peterson 2004).

Active galaxies differ from the so called "normal" galaxies in the amount of energy emitted from their nuclei. The term AGN refers to the energetic phenomena in the central region of a galaxy which cannot be solely or directly produced by stars. These phenomena have been the subjects of intensive astrophysical investigations during the last 3 – 4 decades. As the most luminous objects in the Univese with the most powerful energy release rates and with very compact dimensions, AGN are of the great interest in modern astrophysics. AGN (i.e. quasars) are the brightest known objects and thus, these objects are important for the studies of the early Universe and cosmology in general. For instance, studies of luminosity functions or quasar host galaxies are crucial for understanding the formation and evolution of galaxies in general.

The class of active galaxies contains many different objects, such as quasars, gigantic elliptic radio galaxies, luminous spiral Seyfert galaxies, blazars, etc. General characteristics of all these different types of active galaxies can be described by a unique, so called, unification model of AGN (Antonucci 1993). According to this model, the central engine of AGN consists of a supermassive black hole (SMBH) with mass ranging from 10^5 to 10^9 $M_\odot$ ($M_\odot$ – solar mass), which is surrounded by an accretion disk that radiates in the X-

Send offprint requests to: L. Č. Popović ray band (Fabian et al. 1989). The vast majority of the X-ray sources in the Universe are AGN and their integral emission reflects the history of accretion onto SMBH over cosmic time. Emission lines are usually seen in the X-ray spectra of AGN and the most significant one is the broad emission Fe Kα spectral line (6.4–6.9 keV, depending on ionization state) with asymmetric profile (narrow bright blue peak and a wide faint red wing) which has been observed in a number of type 1 AGN (see e.g. Nandra et al. 2007).

Additionally to the Fe Kα line, the narrow and broad emission lines are present in the optical (and UV) spectra of AGN. Their shapes and intensities give us opportunity to investigate the physical and kinematic properties in the central parts 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 (so called Broad Line Region - BLR) in the central part of AGN (Osterbrock (1989); Krolik (1999); Peterson (2004)). The BELs can be emitted by high and low 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.

Besides the strong emission lines, in spectra of the AGN with BELs, the Broad Absorption Lines (BALs) in the UV part of spectra are present. Approximately 10% of all quasars have spectra with broad, blue-shifted absorption lines with the corresponding outflow velocities which can reach 0.1 – 0.2 c. Usually, the high ionization species, such as C IV λ1549, Si IV λ1397, N V λ1240 and Lyα lines have been observed in the spectra of these quasars. Rarely, some of them also exhibit broad absorption and low ionization lines of Mg II λ2798 and Al III λ1857.

In this paper we give a short overview of possibilities to use the spectral lines of AGN (from the X-ray to the optical part of their spectra) for investigating their physics and geometry. Mainly we present some investigations performed by Group for Astrophysical Spectroscopy (GAS) at Astronomical Observatory in Belgrade. Also, we point out some problems connected to the spectroscopy of AGN.

2. Broad Emission Lines - from Fe Kα to the Balmer lines

2.1. Fe Kα line

This is the strongest line of the X-ray radiation which is observed in the spectra of all types of accreting sources, such as binary black holes and neutron star systems, cataclysmic variable stars and AGN. Tanaka et al. (1995) obtained the first convincing proof for the existence of the Fe Kα line in AGN spectra. This discovery was made after four-day observations of Seyfert 1 galaxy MCG-6-30-15 by Japanese *ASCA* satellite. Iron abundance in the accretion disks of AGN is sufficient to produce very strong emission in this fluorescent/recombination line. Therefore, the Fe Kα line is an important indicator of accreting flows around supermassive black holes of AGN, especially because it is produced in inner parts of their accretion disks.

Generally speaking, the Fe Kα line is produced when plasma is subjected to the influence of the hard X-ray radiation so that one of the two K-shell ($n = 1$, where n is the principal quantum number) electrons of an iron atom (or ion) is ejected following the photoelectric absorption of an X-ray. The threshold for the absorption by neutral iron is 7.1 keV. The resulting excited state decays when an L-shell ($n = 2$) electron drops into the K-shell, releasing 6.4 keV of energy. This energy is either emitted as an emission-line photon (34% probability) or internally absorbed by another electron (66% probability) which is consequently ejected from the iron ion (Auger effect). Therefore the appearance of Fe Kα line in the spectra of AGN indicates presence of hot plasma in the innermost parts of their accretion disks.

The Fe Kα line is rather narrow by itself, but in case when it originates from a relativistically rotating accretion disk of AGN it be-

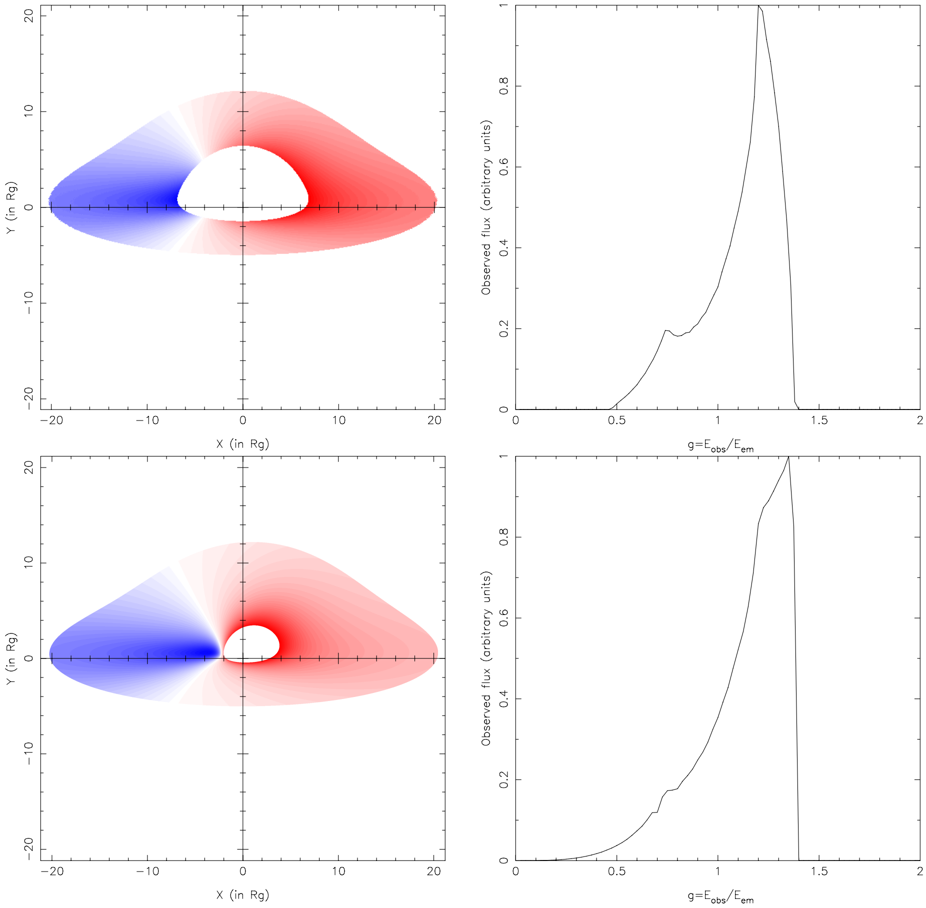

Fig. 1. The emission of an accretion disk (left figures of the panels) and the shape of Fe Kα line (right figures of the panels). Non-rotating (up) and rotating (down) black hole cases are shown (Jovanović & Popović 2009).

comes much broader due to kinematical effects, and then the most broad parts of the line arise from the innermost regions of the disk, where the rotation of emitting material is the fastest (see Fig. 1). Such broadening of the line is very often observed in spectra of Seyfert galaxies and it is one of the main evidences for the existence of a relativistic accretion disk which surrounds their central black hole.

Also, the shapes (or profiles) of the Fe Kα line originating from relativistically rotating accretion disks of AGN are significantly changed due to Doppler boosting and gravitational redshift. If the line originated from an arbitrary radius of a nonrelativistic (Keplerian) accretion disk it would have a symmetrical profile (due to Doppler effect) with two peaks: a "blue" one which is produced by emitting material from the approaching side of the disk in respect to an observer, and a "red" one which corresponds to emitting material from the receding side of the disk. But, taking into account the integral emission in the line over all radii of accretion disk, one can obtain the line with asymmetrical and highly broadened profile (Jovanović & Popović 2009). The "blue" peak is then very narrow and bright, while the "red" one is wider and much fainter (see Fig.

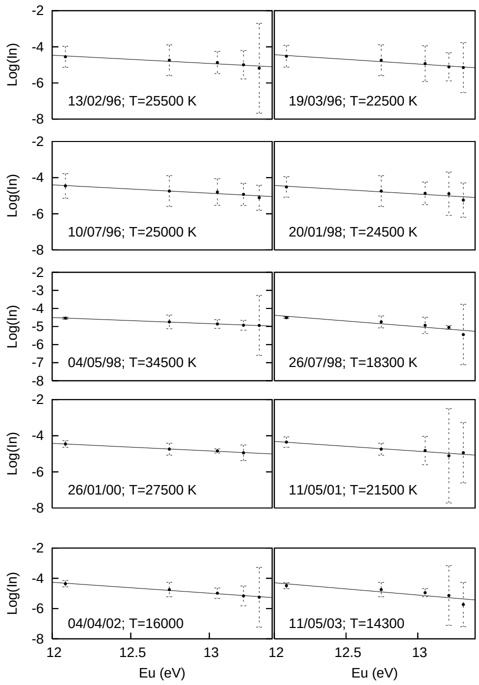

Fig. 2. The normalized intensity as a function of the upper level energy (so called Boltzmann-plot) in the case of NGC 5548 (Popović et al. 2008).

1). Besides, the gravitational redshift causes further deformations of the Fe Kα line profile by smearing the "blue" emission into "red" one.

Since the observed Fe Kα line profiles are strongly affected by such relativistic effects, they represent a fundamental tool for investigating the plasma conditions and the space-time geometry in the vicinity of the supermassive black holes of AGN (for more details see Jovanović & Popović 2009).

2.2. Broad Line Region - Broad Emission Lines

The prominent broad emission lines, visible in the spectra of many AGN (see Fig. 3), originate close to the central power source, in the so called Broad Line Region. Because of its small distance from the power source, the BLR is in strong interaction with the radiation field produced by the central engine and with its gravitational forces. Many interesting details about the physics of processes that are taking place within AGN can be identified in the signal of the BLR, but they suffer from a still missing complete picture of the complex kinematical and thermodynamical properties of the line emitting plasma. Since it is not yet possible to directly observe the spatial distribution of the broad line emitting medium, although many important achievements were obtained in the angular resolution of AGN cores at radio wavelengths, spectroscopic data are still the most useful way to investigate physics within the BLR. The well known Reverberation Mapping (RM) technique, based on multiple spectroscopic observations, provides a reliable way to constrain the volume where the nuclear activity is confined and, thus, to estimate the mass concentration therein (see e.g. Peterson 2008), and references therein).

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); also, a unified model of all AGN was proposed and discussed (e.g. Antonucci 1993). But some unanswered questions concerning the BLR are still present concerning the physics and geometry of the BLR.

(i) **Physics of the BLR**. Since the BLR is located on a relatively small distance 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 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

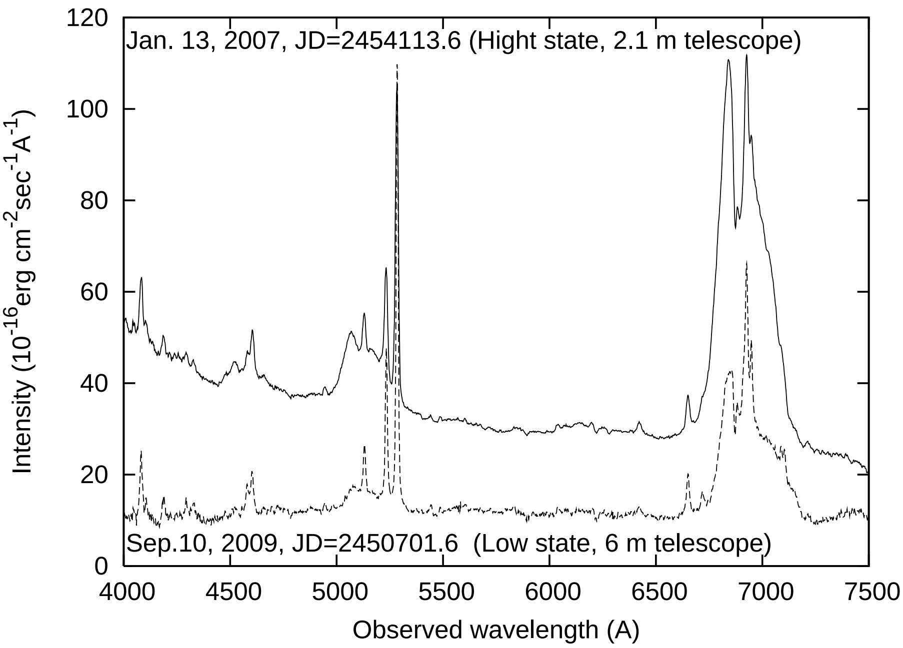

Fig. 3. The spectra in the maximum (up) and minimum (down) of 3C390.3 (see Shapovalova et al. 2009).

UV spectra of AGN indicate that they should originate close to the AGN central 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. Also, around 5% of AGN have spectra with double peaked broad emission lines (e.g. 3C390.3, see Fig. 3), indicating presence of an accretion disk in the BLR, but the number of such objects is insufficient for an indisputable conclusion.

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 $Ly\alpha/H\beta \approx 10$, Osterbrock 1989). But, there are several approaches to combine photoionization with other effects to obtain the line ratios (see more details in Netzer 2008).

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

[1] These lines also can be used to check sophisticated calculation of atomic parameters, see e.g. Dimitrijević et al. (2007)

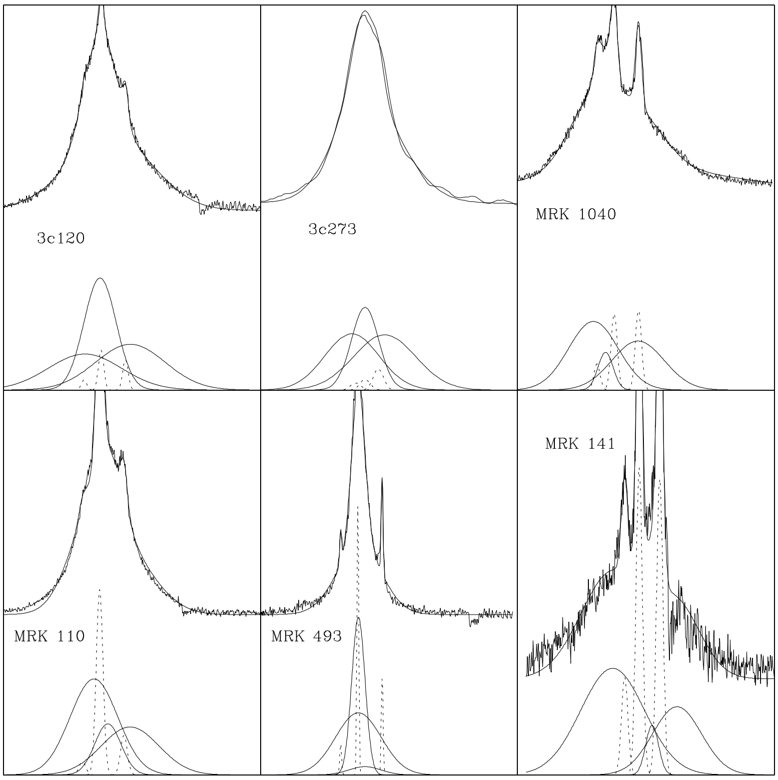

Fig. 4. Decomposition of the lines into broad and narrow components (Popović et al. (2004); Bon et al. (2009a).

ideas about the source of heating for the Fe II emitting gas (see e.g. Kovačević et al. 2009).

To explain line ratios in the optical part of AGN spectra, photoionization, recombination and collisions should 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.

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 (as e.g. Korista & Goad 2004). But, there is a problem to develop a theory that can be applied directly to observations, i.e. to use the measured line ratios or line profiles to have at least a rough estimation of the physical properties in the BLR. There are some indications that in some objects the excitation tempera-

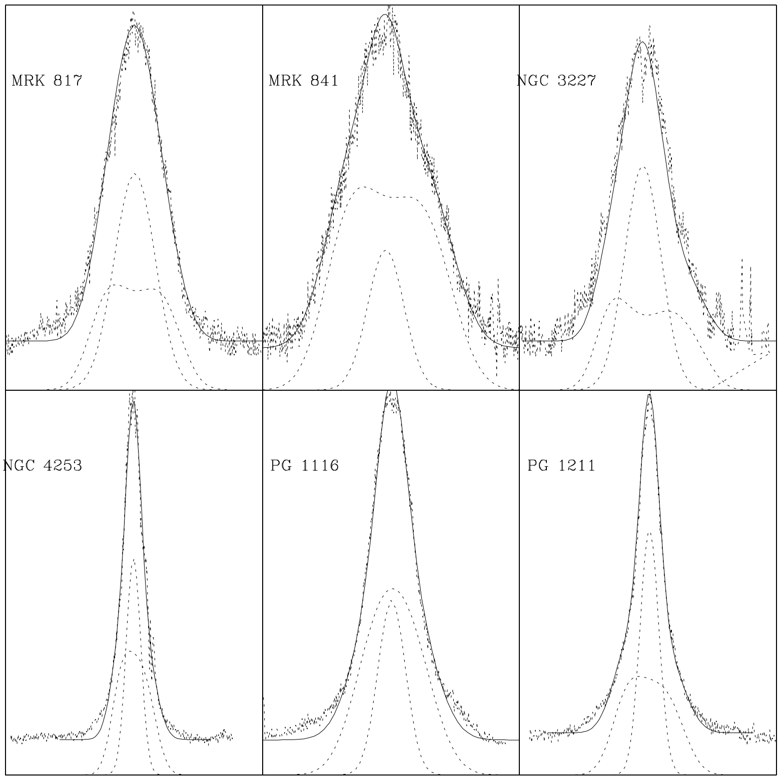

Fig. 5. Decomposition of the BEL shapes in the two components: emission of the disk and an additional emitting region (Bon et al. 2009a).

ture is affecting Balmer line ratios (see Fig. 2), then in this case some estimations of the BLR physical parameters can be performed (see e.g. Popović 2003; Popović et al. 2008; Ilić et al. 2009).

(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 (as it is case for 3C390.3, see Fig. 3), 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. see e.g. Sulentic et al. 2000; Gaskell 2009). 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 first instance, to investigate the BELs one should very carefully subtract the continuum and narrow/satellite lines (see Figs. 4 and 5). This can be very complex and mainly a gaussian decomposition is used (see Popović et al. 2004; Bon et al. 2009a,b).

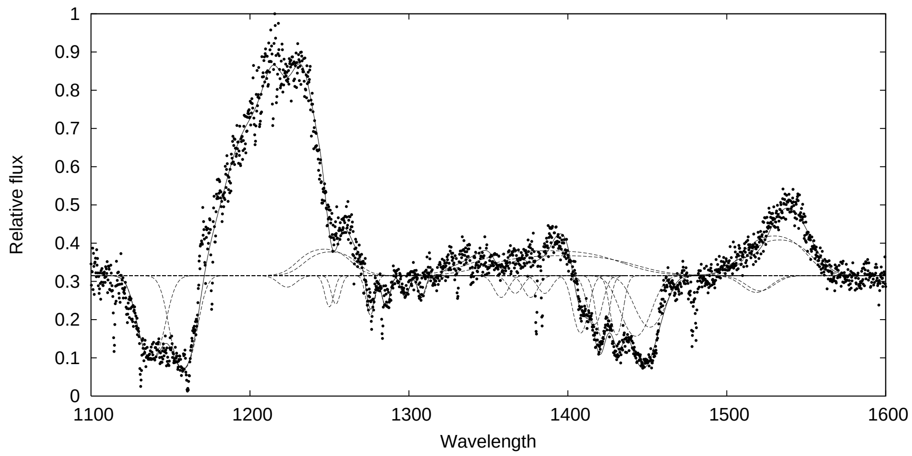

Fig. 6. Decomposition of the BAL shapes in the rotation and random components in the case of BALQSO PG 1254+047 (see Lyratzi et al. 2009).

The rotating accretion disk model (see e.g. Eracleous et al. 2009, and references therein) 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. 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). Also, a Keplerian disk with disk wind can produce single-peaked broad emission lines as normally seen in most of the AGN (Murry & Chiang 1998). 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. 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. 2004; Bon et al. 2009a,b), 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.

It is interesting, that in assumption of the two-component model (disk+smt) to explain single peaked lines, the inclination of the disk tends to have values between 10 and 25 degrees, that could be connected with the obscuration of the torus (in more details see Bon et al. 2009b),

3. Broad Absorption Lines

As it was mentioned in §1, approximately 10% of all quasars are with broad, blue-shifted absorption lines for which the corresponding outflow velocities can reach up to 0.1 – 0.2 c (see Fig. 6). A fundamental issue in the study of the BALR is to determine their geometry and origin. No compelling evidence in favor of a specific picture exists, and the uncertainty in these issues is hampering our attempts to obtain a complete physical model for the flows. One of the widely accepted models is

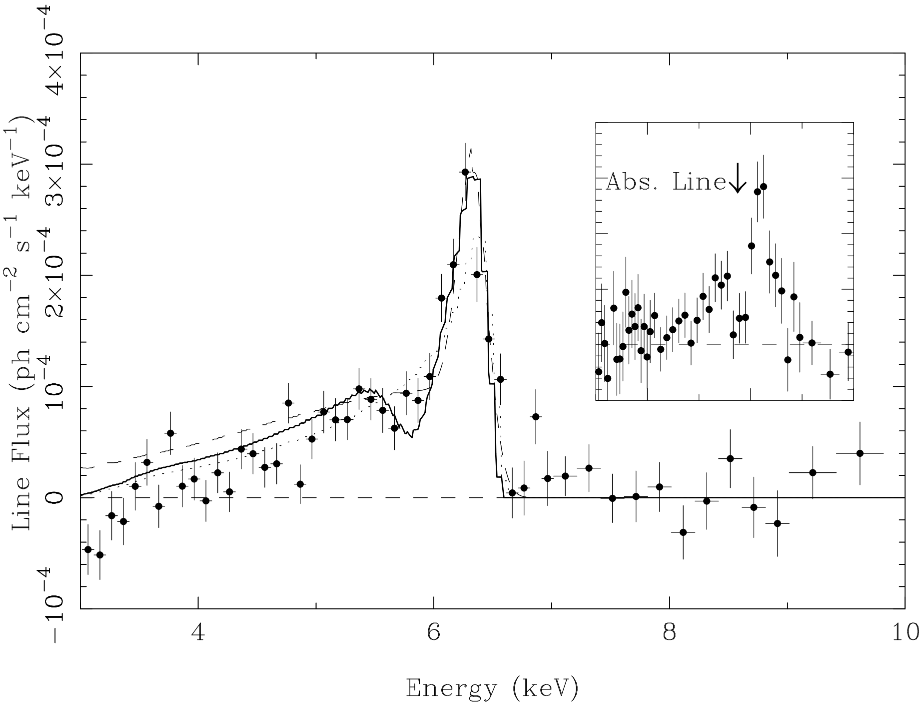

Fig. 7. Absorption component at 5.8 keV in the red part of the Fe Kα line of Seyfert 1 galaxy NGC 3516, observed by *ASCA* satellite (Nandra et al. 1999). The dashed line shows best fit with model of an accretion disk around a rotating (Kerr) black hole.

that of a disk wind creating the BALR (see e.g. Murry & Chiang 1995; Proga et al. 2000; Proga & Kallman 2004).

Investigations of blue-shifted absorption lines showed that around 10% of type I (broad emission line) AGN show gas outflowing from their centers with velocities $\sim 10^{3-4}$ km s^{-1} (Reichard et al. 2003). Such outflows are probably launched from the central engine of quasars (Elvis 2000). The broad absorption lines can be detected mainly in the UV part of AGN spectra, but the X-ray emission of AGN could be also significantly absorbed by an outflowing wind, especially in case of so-called Low Ionization Broad Absorption Line (LoBAL) quasars. Recent observations of such quasars (e.g. Mrk 231 (Braito et al. 2004) and H 1413+117 (Chartas et al. 2004, 2007)) confirmed the presence of X-ray absorbers in these objects. Chartas et al. (2007) found that spectra of H1413+117 (Cloverleaf) quasar show emission features redward of the Fe Kα line rest-frame energy and broad absorption features blueward of this energy, which confirms earlier finding that intrinsic absorption of this quasar could significantly affect its X-ray emission (Chartas et al. 2004). Wang et al. (2001) detected an absorption line at 5.8 keV in nearby Seyfert 1.5 galaxy NGC 4151. A variable absorption line at the same energy has been discovered by Nandra et al. (1999) in NGC 3516 (see Fig. 7) and was interpreted as a Fe K resonant absorption line, redshifted either by infalling absorbing material or by strong gravity in the vicinity of the black hole. Done et al. (2007) found an evidence for a P Cygni profile of the Fe Kα line (see Fig. 8) in narrow line Seyfert 1 galaxies. According to these authors, complex X-ray spectra of these objects show strong "soft excess" below 2 keV and a sharp drop at $\sim$ 7 keV which can be explained either by reflection or by absorp-

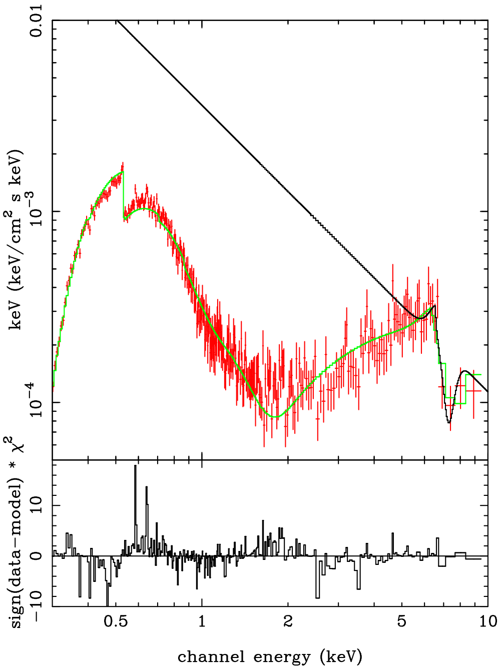

Fig. 8. The full *XMM-Newton* spectrum of 1H 0707-495 with the best-fit model which involves a P Cygni profile for the iron features (Done et al. 2007). The lower panel shows residuals to the fit.

tion from relativistic, partially ionized material close to the black hole. They showed that a sharp feature at ∼ 7 keV results from absorption/scattering/emission of the iron Kα line in the wind. In the case of 1H 0707-495 (Fig. 8), this absorption feature can be satisfactorily fitted by the P Cygni profile (Done et al. 2007).

3.1. Absorption in the Fe Kα line

There are different models of the X-ray absorbing/obscuring regions, like absorbing medium comprised of cold absorbing cloudlets by Fuerst & Wu (2004), but here we will briefly describe the model given by Jovanović & Popović (2007) and Jovanović et al. (2009), since it is developed in order to study how much warm X-ray absorbers can change the Fe Kα spectral line profile, emitted from a relativistic accretion disk of AGN. In this model, absorption region is considered to be composed of a number of individual spherical absorbing clouds with the same small radii, scattered in space so that projections of their centers to the observer's sky plane have bivariate normal distribution (see Fig. 9 left). Intensity of each light ray which passes through some of these absorbing clouds is affected by them according to the value of absorption coefficient, which depends on spectral features, velocity and distribution of absorbing material. Therefore, the resulting line profile could be more or less absorbed by such absorption region. A comparison between the unabsorbed Fe Kα spectral line profile and the corresponding absorbed profile obtained by this absorption model is given in Fig. 9 (right). As it can be seen from Fig. 9, when the X-ray radiation from approaching side of the disk is significantly absorbed/obscured by the absorbing region, there is a very strong absorption of the iron line. In such case the emission Fe Kα line looks redshifted at ∼ 5 keV and is followed by a strong absorption line at ∼ 7 keV (Fig. 9 right), which indicates the P Cygni profile of the iron line. The observed sharp drop at ∼ 7 keV and emission at ∼ 5 keV can be then explained by intrinsic absorption from relativistic, partially ionized material close to the black hole, which mainly cover the approaching side of the relativistic accretion disk. It is interesting that the width and depth of the absorption component strongly depends on the projection of absorption region on the accretion disk. This model can satisfactorily explain the P Cygni profile of the Fe Kα line only if at least a part of approaching side of the accretion disk is partially blocked from our view by the X-ray absorbing/obscuring material, while the rest of the disk is less absorbed/obscured and therefore is visible (Jovanović & Popović 2007; Jovanović & Popović 2009).

3.2. Absorption in the broad UV/optical lines

The broad absorption lines are often observed in the UV spectra, they are very often superposed with broad emission lines. Broad ab-

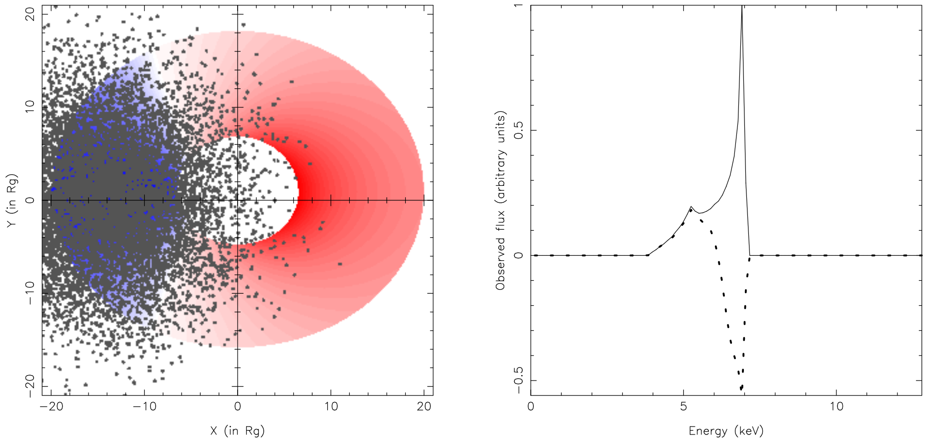

Fig. 9. *Left:* Relativistic accretion disk in the Schwarzschild metric partially covered by a cloud of absorbing material (randomly scattered gray dots). *Right:* Comparison between the unabsorbed Fe Kα spectral line profile (solid line) and corresponding absorbed profile (dotted line) caused by the absorbing/obscuring region presented in the left panel (Jovanović & Popović 2007).

sorption lines may have different shapes, but differences in continua are also present in the spectra of various types of AGN which contain such lines (see e.g. Reichard et al. 2003). A 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).

One of important questions is: what are the physical connections between the BLR and BALR? This is also important since at least a part of the BLR seems to be originated from wind of accretion disk (see Murry & Chiang 1998; Popović et al. 2004). Additionally, one question is: where the BALR is placed with respect to the center of a BALQSO and the Broad Line Region? To answer this question, one should investigate the kinematical properties of the emission and absorption lines.

There are several ways to answer the questions above, as e.g. one can use the models (e.g one as proposed as e.g. in Danezis et al. 2009) and try to explain very complex BAL profiles. As an example in Lyratzi et al. (2009) was found that the BALs seem to be produced at the same place (or even closer) as BELs and that this result is in the favor of the models that assume the forming line region as the region which emits broad emission and absorption lines, as e.g. resonance scattering model.

4. Conclusions

Here we shortly discuss the possibility to use the spectral line intensities and shapes in order to investigate AGN (and quasars as a group of AGN). There are many ways to use the line shapes to conclude about physics and kinematics in the central part of quasars. From one side, Fe Kα line can be used to explore the innermost structure of an accretion disk, while from the other side, optical and UV lines can be used to estimate super-massive black holes and geometry of gas in the BLR. Additionally, absorption lines can give us impression about super wind in the central part of some quasars. Therefore, spectral line shapes and their intensity ratios can be useful tools to learn about the quasar nature.

5. Acknowledgements

The work was supported by the Ministry of Science of Serbia through the project 146002:

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