Publ. Astron. Obs. Belgrade No. 86 (2009), 153 - 160 *Invited lecture*

CENTRAL ENGINE OF ACTIVE GALAXIES AS THE MOST POWERFUL SOURCE OF X-RAY RADIATION IN THE UNIVERSE

P. JOVANOVIĆ and L. Č. POPOVIĆ
Astronomical Observatory, Volgina 7, 11060 Belgrade 38, Serbia
E–mail: pjovanovic@aob.bg.ac.yu

Abstract. A broad emission line Fe Kα at 6.4 keV with asymmetric profile (a narrow bright blue peak and a wide faint red wing) has been observed in a number of type 1 Active Galactic Nuclei (AGN). In some cases the line width corresponds to one third of speed of light, indicating that its emitters rotate with relativistic velocities. Therefore, the line is probably produced in a very compact region near the central black hole (BH) of AGN and can provide us some essential information about the plasma conditions and the space-time geometry in vicinity of the BH. The X-ray radiation of AGN, in the line, as well as in the continuum, has rapid and irregular variability. This variability could be due to disk instability, resulting in perturbations of the disk emissivity, or it could be caused by some external effects, such as gravitational microlensing (especially in the case of gravitationally lensed quasars) and absorption. Here we present a short overview and main results of our recent investigations of the Fe Kα spectral line and X-ray continuum variability.

1. INTRODUCTION

Active galaxies are galaxies hosting a small, highly variable and very bright core (Active Galactic Nucleus), embedded in an otherwise typical galaxy. AGN are powerful sources of radiation in a wide spectral range: from γ rays to radio waves. They derive their extraordinary luminosities (sometimes more than 10^4 times higher than luminosities of "ordinary" galaxies) from energy release by matter accreting towards, and falling into, a central supermassive black hole. According to the unification model of AGN, their central engine consists of a supermassive BH ($10^7 - 10^9 M_\odot$) which is surrounded by an accretion disk that radiates in the X-ray band. Accretion disks could have different forms, dimensions, and emission, depending on the type of central BH, whether it is rotating (Kerr metric) or nonrotating (Schwarzschild metric) BH. They represent an efficient mechanism for extracting gravitational potential energy and converting it into radiation, giving us the most probable explanation for the main characteristics of AGN (high luminosity, compactness, jet formation, rapid time variations in radiation and in the profile of the Fe Kα spectral line).

The X-ray spectrum and variability properties of AGN in most cases could be described with a two-component model consisting of a power-law continuum and a broad Fe Kα line at 6.4 keV (Larsson et al. 2007). The line was discovered in Seyfert 1 galaxy MCG-6-30-15 (Tanaka et al. 1995) and later on observed in a number of

AGN (Nandra et al. 1997, 2007). Its asymmetric profile (a narrow bright blue peak and a broad faint red one) is affected by relativistic effects near the central BH of AGN and therefore, the observed Fe Kα line profiles represent a fundamental tool for investigating the plasma conditions and the space-time geometry in vicinity of the supermassive BH.

Rapid and irregular variability of the observed X-ray emission is a common property of all AGN, but in some cases it cannot be explained by standard model of accretion disk. For example, in addition to the stable 6.4 keV core of the Fe Kα line, a variable "red" feature of the line at 6.1 keV is also detected in NGC 3516 (Iwasawa et al. 2004). This feature varies systematically in flux at intervals of 25 ks and in energy between 5.7 and 6.5 keV. These authors found that the spectral evolution of the "red" feature agrees well with the hypothesis of an orbiting spot in the accretion disk.

The X-ray emission of AGN could be also significantly absorbed by an outflowing wind, especially in the 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. 2007)) confirmed the presence of X-ray absorbers in these objects. Wang et al. (2001) detected an absorption line at 5.8 keV in nearby ($z = 0.0033$) 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 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 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 absorption from relativistic, partially ionized material close to the black hole. They showed that a sharp feature at $\sim$ 7 keV results from absorption/scattering/emission of iron Kα line in the wind. In the case of 1H 0707-495, this absorption feature can be satisfactorily fitted by the P Cygni profile (Done et al. 2007).

Recent observational and theoretical studies suggest that gravitational microlensing can also induce variability in the X-ray emission of AGN, especially in the case of gravitationally lensed QSOs (for more details see e.g. Jovanović (2006), Jovanović et al. (2008) and Popović et al. (2006a) and references therein).

According to the above studies, the X-ray variability of AGN could be due to accretion disk instability, resulting in perturbations of the disk emissivity, or it could be caused by some external effects, like gravitational microlensing and absorption by X-ray absorbers. In order to model the observed X-ray variability of AGN, we developed a model of perturbations of the disk emissivity, a model of absorption region and three models of gravitational microlensing. In the following text we will present a short overview and main results of our recent investigations in this field.

2. MODELING OF ACCRETION DISK EMISSION

The Fe Kα line is originating from the innermost parts of the accretion disk and its shape strongly depends on emissivity law. It is usually accepted that surface emissivity of the disk varies with radius as a power law: $\varepsilon(r) = \varepsilon_0 \cdot r^q$, where ε_0 is emissivity constant and q is emissivity index. Total observed flux is then given by

(Popović et al. 2006a): $F_{\rm obs}(E_{\rm obs}) = \int\limits_{\rm image} \varepsilon(r) \cdot g^4 \delta(E_{\rm obs} - gE_0) d\Xi$, where g is the energy shift due to the relativistic effects: $g = \frac{\nu_{\rm obs}}{\nu_{\rm em}}$ and the rest energy of the Fe Kα line is: $E_0^{FeK\alpha} = 6.4$ keV. $d\Xi$ is the solid angle subtended by the disk in the observer's sky.

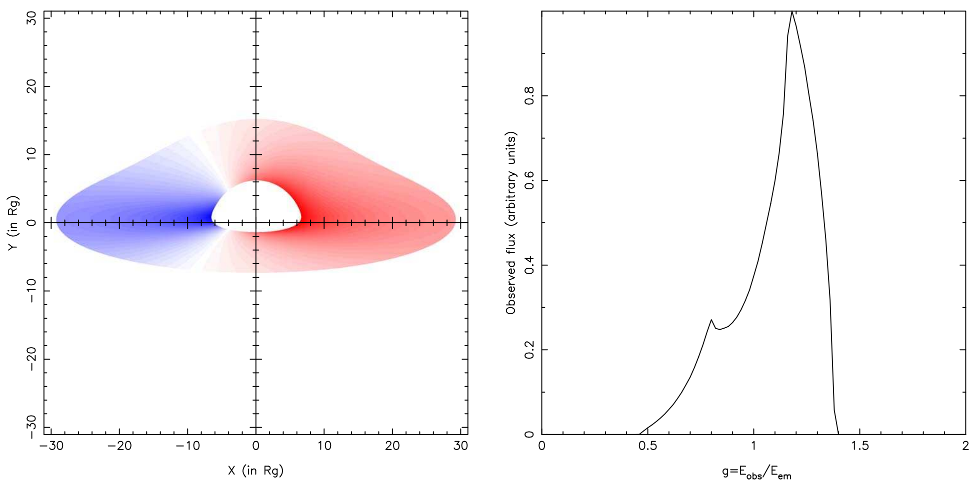

Figure 1: Illustrations of accretion disk (left) and the corresponding Fe Kα line profile (right) in the case of Schwarzschild metric. The disk inclination is $i = 75°$ and its inner and outer radii are $R_{\rm in} = R_{\rm ms}$ and $R_{\rm out} = 30$ R$_{\rm g}$, respectively.

We modeled the emission of an optically thick and geometrically thin accretion disk around supermassive BH using numerical simulations based on a ray-tracing method in a Kerr metric, taking into account only photon trajectories reaching the observer's sky plane in the infinity (see e.g. Popović et al. 2003ab). In this method one divides the image of the disk on the observer's sky into a number of small elements (pixels). For each pixel, the photon trajectory is traced backward from the observer by following the geodesics in a Kerr space-time, until it crosses the plane of the disk. Then, the flux density of the radiation emitted by the disk at that point, as well as the redshift factor of the photon are calculated. In that way, one can obtain the color images of the accretion disk which a distant observer would see by a high resolution telescope. The simulated line profiles can be calculated taking into account the intensities and received photon energies of all pixels of the corresponding disk image. Fig. 1 shows an example of such simulated disk image (left) and the corresponding simulated line profile (right) in the case of the Schwarzschild metric (or equivalently, the Kerr metric with zero angular momentum).

To obtain modeled line profiles, it is necessary to define a number of parameters which describe the line emitting region in the disk, such as constraints for its size, the disk inclination angle, the mass of the central BH and its angular momentum. For that purpose we usually use the results from studies of the observed Fe Kα line profiles in AGN, such as e.g. Nandra et al. (1997). The inner radius $R_{\rm in}$ of the disk cannot be smaller than the radius of the marginally stable orbit $R_{\rm ms}$, that corresponds to $R_{\rm ms} = 6\ R_{\rm g}$ (gravitational radius $R_{\rm g} = GM/c^2$, where G is the gravitational constant,

M is the mass of central BH, and c is the velocity of light) in the Schwarzschild metric and to $R_{\rm ms} = 1.23\ R_{\rm g}$ in the case of the Kerr metric with angular momentum parameter $a = 0.998$. To select the outer radius $R_{\rm out}$ of the disk, we take into account some recent investigations of the Fe Kα line profile showing that it should be emitted from the innermost part of the disk which outer radius is within several tens of $\rm R_g$ (see Popović et al. (2006a) and references therein).

3. RESULTS

In this section we will present the main results of our recent investigations of the X-ray emission of AGN. We will pay attention mostly to the strong gravitational field influence on the Fe Kα line and to the X-ray variability.

3. 1. OBSERVATIONAL EFFECTS OF STRONG GRAVITY IN VICINITY OF SUPERMASSIVE BLACK HOLES

In general, black holes have three measurable parameters (not including the Hawking temperature): charge, mass (and hence gravitational field) and angular momentum (or spin). In the case of supermassive BHs of AGN, only the latter two are of sufficient importance. Our investigations showed that these two parameters are responsible for several effects which can be detected in the observed Fe Kα line shapes (see e.g. Jovanović and Popović 2008a).

In order to study the size of the Fe Kα line emitting region, as well as its location in the disk, we assumed that the line is emitted from a region in form of narrow ring (Jovanović and Popović 2008a) with width = 1 $R_{\rm g}$, located between: a) $R_{\rm in} = 6\ \rm R_g$ and $R_{\rm out} = 7\ \rm R_g$ and b) $R_{\rm in} = 50\ \rm R_g$ and $R_{\rm out} = 51\ \rm R_g$. The corresponding results are presented in Fig. 2. From this figure one can see how the Fe Kα line profile is changing as a function of distance from the central BH. When the line emitters are located at the lower radii of the disk, i.e. closer to the central BH, they rotate faster and the line is broader and more asymmetric (see Fig. 2 top). If the line emission is originating at larger distances from the BH, its emitting material is rotating slower and therefore the line becomes narrower and more symmetric (see Fig. 2 bottom). In majority of AGN, where the broad Fe Kα line is observed, its profile is more similar to the modeled profile as obtained under assumption that the line emitters are located close to the central BH (Jovanović and Popović 2008a).

3. 2. X-RAY VARIABILITY DUE TO PERTURBATIONS OF DISK EMISSIVITY

In order to model the observed variability in the Fe Kα line profiles and intensities, we first consider the perturbations in the accretion disk emissivity. Many processes in the accretion disk may lead to perturbations in its emissivity, such as self gravity, disk-star collisions and baroclinic vorticity (Flohic and Eracleous 2008). For emissivity perturbing region we used bright spot model given by Jovanović and Popović (2008b).

An example of disk perturbed emissivity is presented in the left panel of Fig. 3 and the corresponding perturbed and unperturbed profiles of the Fe Kα line are given in the right panel of the same figure. As one can see from Fig 3, only "red wing" of the Fe Kα line is perturbed while the "blue" one and the line core stay nearly constant. Thus, this model could satisfactorily explain the observed variations of the Fe Kα line flux. Besides, we are able to obtain the realistic durations of disk

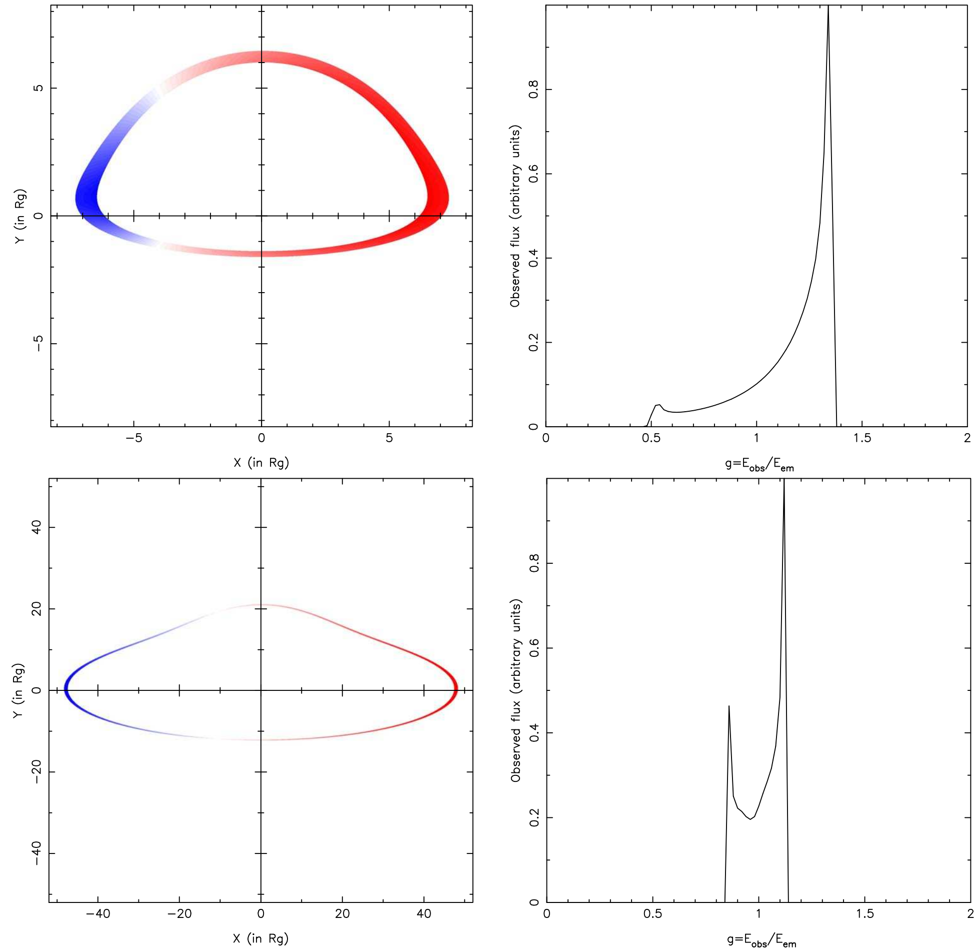

Figure 2: The same as in Fig. 1 but for the Fe Kα line emitting region in form of narrow ring with width $= 1R_{\rm g}$, extending from: $R_{\rm in} = 6$ R$_{\rm g}$ to $R_{\rm out} = 7$ R$_{\rm g}$ (top) and $R_{\rm in} = 50$ R$_{\rm g}$ to $R_{\rm out} = 51$ R$_{\rm g}$ (bottom).

emissivity perturbations when we assume central supermassive black hole with mass $M_{BH} = 1 \times 10^9 M_\odot$ (Jovanović and Popović 2008b).

3. 3. X-RAY VARIABILITY DUE TO ABSORPTION BY WARM X-RAY ABSORBERS

We also developed a model of the X-ray absorbing/obscuring region (see Jovanović and Popović 2007) in order to study how much warm absorbers can change the Fe Kα spectral line profile, emitted from a relativistic accretion disk.

In this model, absorption region is considered to be composed of a number of individual spherical absorbing clouds with the same small radii (see Fig. 4, left). A comparison between the unabsorbed Fe Kα spectral line profile and the corresponding absorbed profile obtained by this absorption model is given in Fig. 4 (right). As it can be seen from Fig. 4, when X-ray radiation from approaching side of the disk is

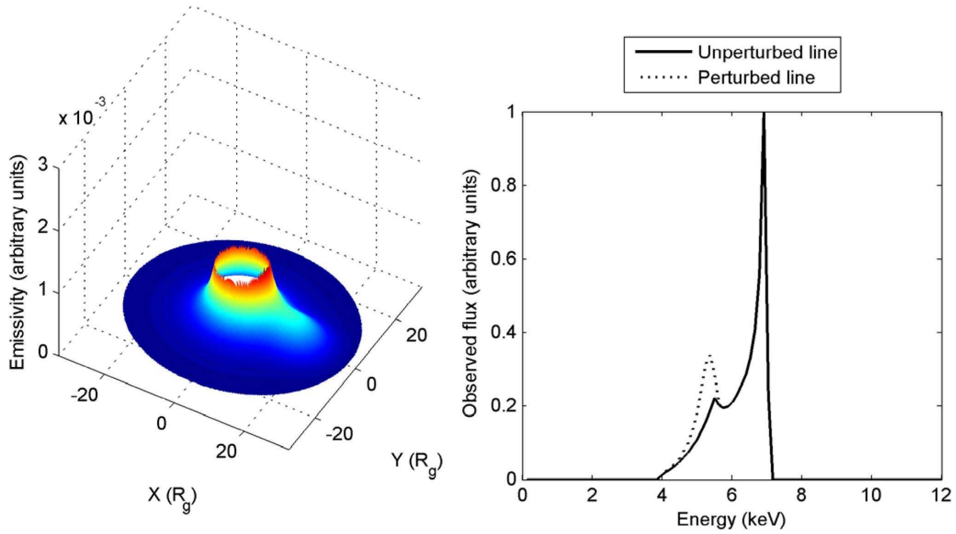

Figure 3: *Left:* The shape of perturbed emissivity of an accretion disk in Schwarzschild metric for the following coordinates of perturbing region: $x_{\mathrm{p}} = 20\ R_{\mathrm{g}}$ and $y_{\mathrm{p}} = 0$ and its widths: $w_{\mathrm{x}} = w_{\mathrm{y}} = 7\ R_{\mathrm{g}}$. *Right:* The corresponding perturbed (dashed line) and unperturbed (solid line) Fe Kα line profiles.

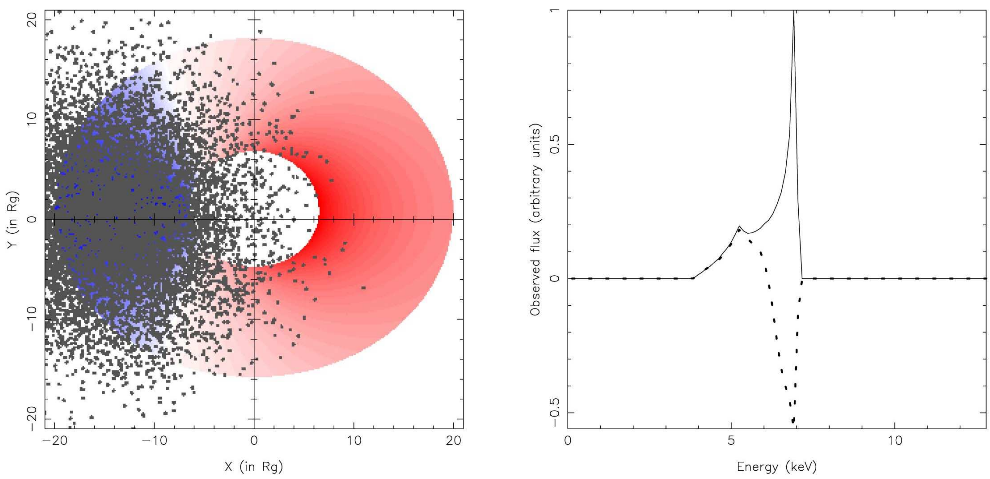

Figure 4: *Left:* Relativistic accretion disk in Schwarzschild metric partially covered by a cloud of absorbing material (randomly scattered gray dots). *Right:* Comparison between the unabsorbed Fe Kα spectral line profile (solid line) and the corresponding absorbed profile (dotted line).

significantly absorbed/obscured by absorption 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. 4, right), which indicates

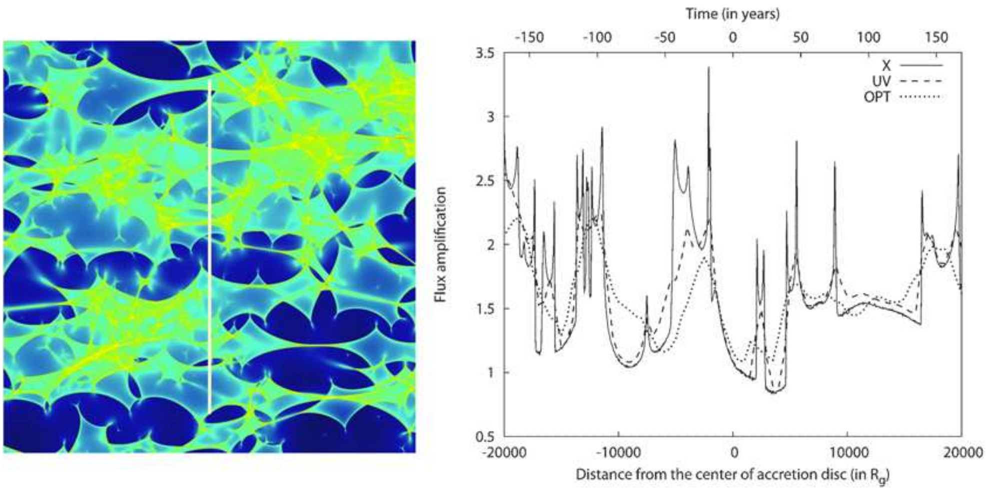

Figure 5: *Left:* Magnification map of a "typical" lens system, where the white solid line represents a path of an accretion disk center. *Right:* Variations in the X-ray (solid), UV (dashed) and optical (dotted) spectral bands corresponding to the path in the magnification map of a "typical" lens system (left).

the P Cygni profile of the iron line. Thus, our model can satisfactorily explain the P Cygni profile of the Fe Kα line in the case when 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 and Popović 2007).

3. 4. X-RAY VARIABILITY DUE TO GRAVITATIONAL MICROLENSING

Gravitational microlensing could have a significant influence on detected X-ray radiation of AGN, causing the Fe Kα line and X-ray continuum variations. We studied the influence of microlensing on an accretion disk emission using three microlensing models: point-like microlens, straight-fold caustic and quadruple microlens (i.e. caustic network or microlensing pattern). For more details about these models see e.g. Popović et al (2003ab, 2006ab), Jovanović (2006), Jovanović et al. (2008) and references therein. Our results show that even small mass gravitational microlenses can produce significant variations and amplifications of the Fe Kα line and X-ray continuum fluxes, and that these amplifications can be significantly larger than the corresponding effects on optical and UV emission lines and continua (Jovanović 2006).

Fig. 5 provides an example of a magnification map (left) for a "typical" lens system (i.e. a lens system where the redshifts of microlens and source are: $z_l = 0.5$ and $z_s = 2$) and the corresponding X-ray, UV and optical continuum variations (right). The light curves in the right panel of Fig. 5 are produced when an accretion disk crosses over the magnification pattern presented in the left panel of the same figure, along the path denoted with the white solid line.

As one can see from Fig. 5 (right), the variations of the X-ray continuum due to microlensing are much stronger and faster in comparison to the variations in UV and optical spectral bands (Jovanović et al. 2008).

4. CONCLUSIONS

We developed a model of an accretion disk around a central supermassive BH in AGN using numerical simulations based on a ray-tracing method in Kerr metric. This model allows us to study the X-ray radiation from an accretion disk and to determine the space-time geometry (metric) and plasma conditions in vicinity of the central supermassive BH of AGN. In order to analyze the observed variability of the accretion disk emission we developed: a model of disk perturbing region, a model of X-ray absorption region and three models of gravitational microlenses (point-like, caustic and magnification map).

We found that our models can explain the observed line shapes in different objects. Moreover, the behavior of the Fe Kα line variations can indicate the processes which are in the background of these variations, such as disk perturbations, gravitational microlensing and absorption. In the future work, we will model the observed Fe Kα profiles in order to estimate the disk parameters, as well as the nature of the X-ray variability.

Acknowledgments

This work is a part of the project (146002) "Astrophysical Spectroscopy of Extragalactic Objects" supported by the Ministry of Science and Technological Development of Serbia.

References

Braito, V., Della Ceca, R., Piconcelli, E., Severgnini, P., Bassani, L., Cappi, M., Franceschini, A., Iwasawa, K., Malaguti, G., Marziani, P., Palumbo, G. G. C., Persic, M., Risaliti, G., Salvati, M.: 2004, *Astron. Astrophys.*, **420**, 79.

Chartas, G., Eracleous, M., Dai, X., Agol, E., Gallagher, S.: 2007, *Astrophys. J.*, **661**, 678.

Done, C., Sobolewska, M. A., Gierliński, M., Schurch, N. J.: 2007, *Mon. Not. R. Astron. Soc.*, **374**, L15.

Flohic, H. M. L. G., Eracleous, M.: 2008, *Astrophys. J.*, **686**, 138.

Iwasawa, K., Miniutti, G., Fabian, A. C.: 2004, *Mon. Not. R. Astron. Soc.*, **355**, 1073.

Jovanović, P.: 2006, *Publ. Astron. Soc. Pacific*, **118**, 656.

Jovanović, P., Popović, L. Č.: 2007, *AIP Conf. Proc.*, **938**, 76.

Jovanović, P., Popović, L. Č.: 2008a, *Fortschr. Phys.*, **56**, No. 4 5, 456.

Jovanović, P., Popović, L. Č.: 2008b, *Publ. Astron. Obs. Belgrade*, **84**, 467.

Jovanović, P., Zakharov, A. F., Popović, L. Č., Petrović, T.: 2008, *Mon. Not. R. Astron. Soc.*, **386**, 397.

Larsson, J., Fabian, A. C., Miniutti, G., Ross, R. R.: 2007, *Mon. Not. R. Astron. Soc.*, **376**, 348.

Nandra, K., George, I. M., Mushotzky, R. F., Turner, T. J. and Yaqoob, T.: 1997, *Astrophys. J.*, **477**, 602.

Nandra, K., George, I. M., Mushotzky, R. F., Turner, T. J., Yaqoob, T.: 1999, *Astrophys. J.*, **523**, L17.

Nandra, K., O'Neill, P. M., George, I. M., Reeves, J. N.: 2007, *Mon. Not. R. Astron. Soc.*, **382**, 194.

Popović, L. Č., Jovanović, P., Mediavilla, E. G. and Muñoz, J. A.: 2003a *A&AT*, **22**, 719.

Popović, L. Č., Jovanović, P., Mediavilla, E. G., Zakharov, A. F., Abajas, C., Muñoz, J. A. and Chartas, G.: 2006a, *Astrophys. J.*, **637**, 620.

Popović, L.Č., Jovanović, P., Petrović, T., Shalyapin, V. N.: 2006b, *Astron. Nachr.*, **10**, 981.

Popović, L. Č., Mediavilla, E. G., Jovanović, P., Muñoz, J. A.: 2003b, *Astron. Astrophys.*, **398**, 975.

Tanaka, Y., Nandra, K., Fabian, A. C., Inoue, H., Otani, C., Dotani, T., Hayashida, K., Iwasawa, K., Kii, T., Kunieda, H., Makino, F., Matsuoka, M.: 1995, *Nature*, **375**, 659.

Wang, J., Wang, T., Zhou, Y.: 2001, *Astrophys. J.*, **549**, 891.