Active Galactic Nuclei, Seyfert type 1 Galaxies and Relativistic Broadened Lines

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Abstract

It is generaly agreed, that a picture of galactic nuclei is so, that a supermassive black hole reside in its centre. In active galactic nuclei (AGN) accretion discs form around the core and provide most of the radiation emerging from that region and basically also from whole galaxy. According to this scheme, intense X-rays originate just a few gravitational radii from the black hole horizon and provide to us a great insight to the proceses in the vicinity of supermassive black hole. Spectral lines originating from the accreting material can describe also the kinematics of material in the disc, most notably the K-α line of iron throught detailed X-ray spectroscopy.

In this astronomy project we sumarize and describe the nature of AGNs and this spectra. In the theoretical part of the project, we focus on active galactic nuclei which can be observed as Seyfert galaxies. Because it is impossible to observe the X-ray spectra on the Earth, the

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practical part is divided in two parts. In first we concentrate to use, operate the Vega telescope at the Golovec observatory (Ljubljana, Slovenia), look for Seyfert galaxies in visible band of spectra and with he aim of CCD imaging to present some pictures of bright types of these galaxies. In the second part we use the data observed by Chandra X-ray observatory of Seyfert type I galaxy MCG-6-30-15 and with the aim of software Spex (for the analysis and interpretation of cosmic X-ray spectra) to simply repeat the fitting of data to Laor line profile model $Laor : 1991 : APJ$. At the end of second part we also modeled graphs with prof. Čadež - Calvani model and graphs compared with graphs thats we made in Spex.

Key words: accretion, accretion discs, black hole, supermassive black holes, line: profiles .

1 Theoretical part

In this part we describe the nature of black holes, esspecially supermassive black holes and existence of their accretion discs. Then we deal with AGNs, later in connection with Seyfert galaxies. We describe the background of their accretion processes and nature of spectral lines. In connection to our practical part, we are concentrating to nature of broadened lines and reasons of broadening in Seyfert type I galaxies.

1.1 Active galactic nuclei and quasars

A strange radio source 3C48 was observed in 1960 with radiotelescope at Jordell Bank observatory $GreenMatt : 1963 : firstquasar$. The strange was its angular size less than 1”. With aim of the 5-meters telescope at Mount Palomar, the faint bluish optical source was detected as its counterpart which looked like a star. Spectra of this object was strange because there was no other object with like spectral lines yet observed. In next years, there were observed many so like stars objects - quasi star objects, which were named quasars.

It was found, that strange spectra are still made by standard spectral lines of hydrogen, oxygen,... So the same atoms of excited gas as can be observed in near stars. But their wave lengths were shifted so highly to the red size of spectra (tens of percents), that from Dopler principle must move apart from us with velocities similar to speed of the light (in first quasars it was 16% - 40% c).

So these high velocities said, that sources cannot be in our Galaxy, but have to belong to the farthest parts of the Universe in which are moving away from us due to the cosmological expansion of the Universe. From the Hubble law is the amount of red shift of the object directly proportional to the distance of the object. And from these calculations it arises, that first observed quasars have to be 2 - 5 bilion light years away. But this also have the only interpretation, that objects so far away must have its shining power hundred times of brightest galaxies! But there were also found, that luminosity is variable in scales of a month $EdeMalk : 1987 :$ *AGNvariability*. And this must means, that the region is less than one light month, so milion times smaller than size of ordinary galaxies. Radiation comes from very massive compact object which is among by hot gas drived by some very energetic source. It shows, that this engine should be a big black hole. Thats because (as we will describe later), black hole can transform mass of the surrounding gas falling on the black hole to thermal radiation which can be later changed also to other types of radiation and so to energy. This "gravitational aggregate" can have very high effectivity, much bigger than energy axtracted from the matter through the thermonuclear processes.

Yet in past, in fact from 1930s, radio sources started to be detected from the Universe $Jansky:1933:radiouniverse$. Later, using radio-interferometry principle with the aim of more radio antennas was possible to improve the resolution and radio galaxies were discovered. First, it was thought that it should be the result of collision of two galaxies, but later it was shown, that it is in all cases only one galaxy from its centre some lobes outgoes and emits radio waves. Detailed atlas of such galaxies was build by Carl Seyfert $Seyfert:1943:NucelarEmiss$ and from those times, these galaxies are called Seyfert galaxies.

Near sources nuclei, these lobes has a form of narrow colimated jets of very energetic particles, which are in bigger distances slowed down by intergalactic gas and dust, and emits radio waves from huge formed lobes which are in lenght tens to hundreds kiloparsecs. Observed geometry of these jets reveal, that they have a stable geometric axis with direction not changed at least in $10^6 - 10^8$ years $ullman:1986:cerne-diry$. So the source of these jets have to be very massive rotating object which angular momentum by its gyroscopic effect warrants so stable axis. Later, we will see that between these active galactic nuclei and quasar is close connection.

1.2 Acretion discs in AGNs

The most important process of interaction of black holes with their neighbourhood is acretion[1]. Surrounding material, mostly gas, is by strong gravitational field attracted into the black hole and due to the high adiabatic contraction and braking processes because of viscous friction (there also acts turbelences, shock waves, etc.) is warmed to very high temperature. A strong emission of ultraviolet and optical light but also X-ray radiation is emited. Due to the acretion is otherwise non radiating black hole become highly radiating object (strictly speaking it is the gas which radiate the electromagnetic radiation).

As the most simple type of accretion, we should describe the spherical accretion, which come on Schwarzschild black hole that is surrounded by non-rotating cloud of matter (gas). Acretion flow is amount of gas consumed by the black hole per unit time. Then if the acretion flow $\frac{\mathrm{d}M_A}{\mathrm{d}t}$ is high enought, it will be warmed by viscous disipation and adiabatic contraction to high temperature

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[1] Oposite to this, the smallest manifestation of black hole to its vicinty is the quantum evaporation, which is in physical real situations almost negligable (if we do not count primordial or microscopic black holes).

and part of energy will be radiated by electromagnetic waves. Gravitational radiation will not apply, because the matter is not distributed in way when quadrupole moment is changing in time (in spherical case is strictly zero). In spherical accretion is the effectivity of transformation of matter to radiation quite low, so spherical accretion could not be the source of radiation in quasars.

Spherical acretion is the most simple case. It is a model which is in nature not realized. In real, the particles of matter will in acretion always some angular momentum with respect to the black hole center. If they should not interact, they movement will obey circullar trajectories around the black hole. But especially in case of AGNs (or also in binary systems) will accreting material posseses quite big angular momentum, bigger than in cases of circular orbits near the horizon. In this case, absorbed material will give to grow to a disc object called **acretion disc**. In this accretion disc, the gas is orbiting around the black hole on gradually descending quasi-circular orbits in so, hat radial velocity of descending of particles of the gas will be much lower than its orbital velocity.

1.2.1 Thin accretion disc

If the black hole is rotating with significant angular momentum J, there will be, due to the intertial frame dragging, accretion disc around the black hole always corotating and situated in the equatorial plane of black hole. Orbiting gas, no matter if comes from different directions ($\theta \neq \frac{\pi}{2}$), is due to the inertial dragging pulled on the equatorial plane of the rotating black hole. If the mass of the accreting disc is much smaller than the mas of the black hole (so we can neglect the mass of the disc) and accretion flow is not too high, the disc will be termed as “thin” and his thicknes will be much smaller than its radius.

1.2.2 Thick accretion disc

Particles of gas in the accretion disc are moving around approximately circular geodetical orbits. In the inner trajectories are the particles moving more quickly than on outer trajectories (this arises from Keplerian laws). But in cases of collisions between particles on neighbour orbits, inner particles are slowed and outer are speeded and angular momentum is transfered to the outer parts of the disc. Gas is warmed and energy is emmited in form of radiation out of the disc.

By the viscous friction, particles are slowed on inner trajectories and radius of their orbit is slowing down to the black hole. When touches the marginaly stable circular orbit ($r = r_{ms}$) which is the inner boundary of the accretion disc, gas is falling on the black hole. If there are no inhomogenities in the disc, no gravitational radiation is emited (there is also no change of quadrupole moment with time).

In the state of equilibrium is the total radiated power equal to amount of energy, which is generated by all particles in the disc per unit time. Every particle of gas with mass $\mathrm{d}M$ throught its whole way in disc from the infinity (or from distance on which we can neglect the binding energy) on the spiral orbit to the marginaly stable orbit (r_{ms}) will emit the amount of energy which its have on the r_{ms}. The total luminosity of the disc is

$$L = (1 - \bar{E}_{ms})c^2 \frac{\mathrm{d}M}{\mathrm{d}t} \,, \tag{1}$$

where $\frac{\mathrm{d}M}{\mathrm{d}t}$ is the total accretion flow, $\bar{E}_{ms}$ is specific energy on the r_{ms} orbit. Effectivity of the transformation of rest mass to the energy depends on the specific energy of marginaly stable orbit. The effectivity for Schwarzschild black hole is 5,72% but for extremly rotating Kerr black hole it is almost 42,26% $ullman : 1986 : cerne - diry$!

If the black hole has lower rotation and so energetical effectivity of accretion disc around 6%, this effectivity will rise as the black hole is accelerated in rotation due to the angular momentum from acreted material. Theoreticaly the black hole can be drive to extremal state where $J = M^2$ (which is the boundary given by 3. law of thermodynamic of black holes). In fact, part of the radiation from accretion disc is consumed by black hole and this consumed radiation slowing down rotation little bit. In this consequences could be the maximal rotation lower than extremal rotation and the boundary effectivity will be around 30%.

Accretion discs can be formed also around neutron stars or white dwarfs, but their energetical effectivity is much lower than in case of black holes (specific binding energy is very small at the surface of these stars).

In cases of highly radiating accretion discs, esspecially when the radiation is near to the Edington luminosity

$$L_{ED} = \frac{4\pi c G M m}{\sigma_T} \,, \tag{2}$$

($\approx 1,3 \cdot 10^{31} \mathrm{M}/\mathrm{M}_{\odot} [\mathrm{J.s}^{-1}]$) then the pressure of radiation dominate above the pressure of gas. The disc due to this dominating pressure becomes to thick. We get the thick accretion disc.

Shape and form of the thick accretion disc is visualized at fig. 1 on the following page. Disc is still thin at outer parts, in big distances from the black hole and also in fact at the inner margin where the matter flows to the black hole. There exists various cusps $Stu : 2005 : MODPLA :$ but allways forms a thin overflow on black hole. Inner edge of the accretion disc lies lower than typical thin accretion disc. It is situated below the marginaly stable circular orbit r_{ms}, but above the marginaly stable **photon** circular orbit r_f where is pressed due to the presure gradient. The total power output is still in form of (1), but instead of energy $\bar{E}_{ms}$, there is a specific energy of the inner edge of the accretion disc. The more higher is the accretion flow $\frac{\mathrm{d}M}{\mathrm{d}t}$, the more thick is the disc, the more steeper are the wals of accretion disc and the more is the inner edge moving to the marginaly stable photon circular orbit r_f. As the accretion flow growing, radiative outflow growing also and the effectivity of accretion is degressing a little bit, because the consumption of the matter by the black hole originate from lower orbits than marginaly stable circular orbit r_{ms} which has the biggest binding energy.

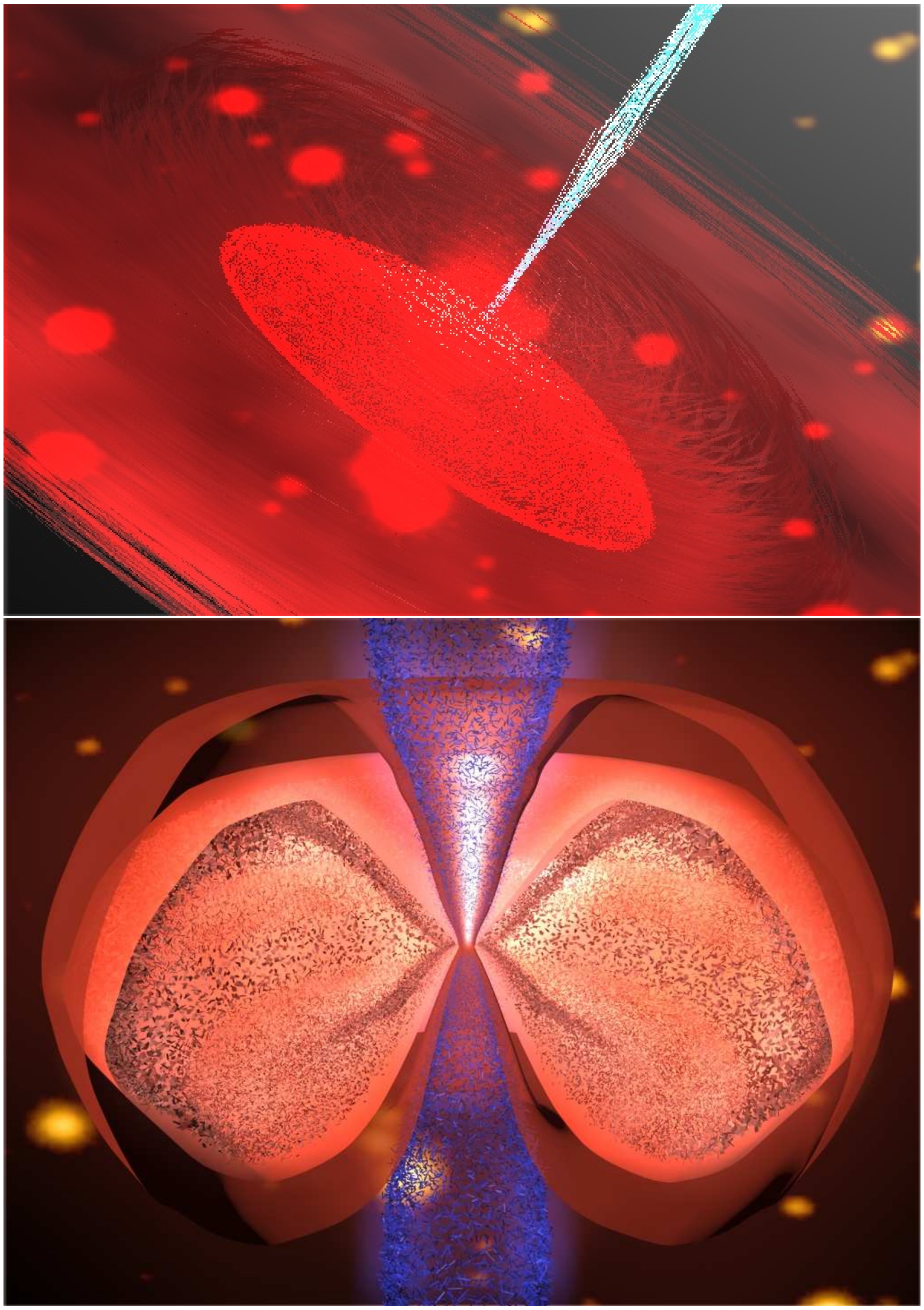

Figure 1: Visualisation of a black hole *Petrasek* : 2005 : *Bezovec* with the thick accretion disc on the basis of *StuSla* : 2005 : *CQG*. Visualisation is made as a approximation of equipotential surfaces in the Cinema 4D software. Upper picture shows thin outer parts of the disc, inner hot area and colimated jet. The lower picture visualise throught the equipotential surfaces the form and shape of thick accretion disc. The pictures has no scientific relevance.

For very high accretion flows, there exist extremly thick accretion discs which has very steepy inner walls. From these walls is most of the radiation emited. There exist multiply absorbtions, scatterings and reemissions of radiation. Resulted radiation is highly anisotropic and is emited mostly alonside of rotational axis. In some cases, when the discs is very thick, the flow of radiation can exceed the Edington luminosity and if the black hole is turned to us in direction of one rotational axis, we see quasar.

The vision of thick accretion disc around the black hole quite naturaly describes the most of features of quasars and active galactic nuclei and also less luminous siblings of quasars - Seyfert galaxies.

In summary, in present is the most realistic model of kvasar and Seyfert galaxy an extremly active nuclei of galaxy which is collapsed into the black hole of mass $\sim 10^6 - 10^9 \mathrm{M}_\odot$. Around this supermassive black hole, the thick accretion disc is formed from the interstellar matter and collapsed stars. In this disc the gravitational binding energy is transformed into the radiation energy. This active nuclei emits the radiation more intensively than the whole galaxy. Due to the colimation of the radiation along the rotational axis, the selective principle plays its role. We see mostly those quasars, which axis of rotation is directed to us. In case of near and less luminous Seyfert galaxies, we see diferent radiation which differs mainly in its spectra.

1.3 Spectral lines of Seyfert galaxies

So there exist different classes of AGNs, sorted by their observed properties. Seyfert galaxies, discovered by Carl Seyfert in the 1940s, are spiral galaxies with luminous, variable nuclei that have strong emission lines in their spectra. Seyfert galaxies have nuclei with $L \approx 10^{10} - 10^{12}\,\mathrm{L}_\odot$. As this, Seyfert galaxies represent the lower-luminosity ($M_{bol} > -23$), radio-quiet section of the AGN family, being less powerful than quasars. There are over 10,000 Seyfert galaxies known; it's estimated that about 1% of bright spiral galaxies are Seyferts. As with all AGN, Seyfert galaxies show strong X-ray emission, which can exhibit rapid variability over 1000s seconds (Mushotsky et al. 1993). The UV and optical continua also vary, but over periods of days (e.g., Edelson, Pike & Krolik 1990), while the IR emission varies only a little, over timescales of months $EdeMalk : 1987 : AGNvariability$. The speed of these changes indicates that the X-rays must be produced in the innermost regions of the nucleus, while the other emission originates further out. Seyfert galaxies, although they all have strong emission lines, have interesting differences among their spectra. Seyfert 1 galaxies have extraordinarily broad Balmer emission lines[2]. If the broadening of the emission lines is due to Doppler shifts of hot gas in motion, it must represent speeds of $v \approx 5000 - 10,000\,\mathrm{km}\cdot\mathrm{s}^{-1}$. By contrast, Seyfert 2 galaxies have much narrower Balmer emission lines. The width of the absorption lines in a Seyfert 2 galaxy correspond to only $v \approx 200 - 400\,\mathrm{km}\cdot\mathrm{s}^{-1}$. If the emission lines in a

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[2] The Balmer series or Balmer lines in atomic physics, is the designation of one of a set of six different named series describing the spectral line emissions of the hydrogen atom.

Seyfert galaxy come from gas orbiting a supermassive black hole, then the light from Seyfert 1 galaxies comes from much closer to the event horizon, where the orbital speeds are higher.

These emission lines may come from the surface of the accretion disk itself, or may come from clouds of gas illuminated by the central engine in an ionization cone. The exact geometry of the emitting region is difficult to determine due to poor resolution. However, each part of the accretion disk has a different velocity relative to our line of sight, and the faster the gas is rotating around the black hole, the broader the line will be.

Only Seyfert type 1 objects - that is, those which show both forbidden and (broader) permitted lines - are being considered in this project. Osterbrock (1981) introduced intermediate classifications, with the notation Sy1.5, 1.8 and 1.9, where the strength of the broad line component decreases as the numerical suffix increases.

An accretion disk described exactly by the standard model produces a relatively soft, quasi-thermal spectrum (dominated by optical/UV radiation or sometimes by soft X-rays). However, accreting black hole systems often exhibit power-law components to their spectra which extend to hard X-ray energies (above the 1 keV). A promising mechanism for producing such a spectrum is the inverse Compton scattering [135,136].

1.4 Broadened lines of Seyfert type I galaxies

Nature has provided us with a well-understood and extremely useful spectral diagnostic of matter in the near vicinity of astrophysical black holes. Relatively cold matter in the near vicinity of an black hole will can be irradiated by a spectrum of hard X-rays [21,22]. The result can be a spectrum of fluorescent emission lines, the most prominent being the K-α line of iron at an energy of $6.4 - 6.97\,\mathrm{keV}$ (depending upon the ionization state of the iron) [23{25]. When the ASCA (Advanced Satellite for Cosmology and Astrophysics) was launched in february 1993 we get a capability to identify this lines and measure their spectral profile. It is now widely accepted that the line originates from material that is just a few gravitational radii from the black hole, and has a profile that is shaped by (relativistic) Doppler shifts and gravitational redshift effects. Investigating these spectral features in X-ray luminous black hole systems has given us the clearest window on the physics that occurs in the immediate vicinity of astrophysical black holes.

2 Practical part - optical observation

In our project we have been to Golovec observatory two times. Our target was the brightest Syfert galaxy M106 and quite accesible NGC3077. Unfortunately both Syfert type 2 galaxies as no Seyfert type 1 galaxy below the 15 mag was found on the sky in present time.

3 Past and current X-ray observatories

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Figure 2: M106 taken in optical spectra at Crni vrh observatory. Image from archive.

Figure 3: NGC3077 taken in optical spectra at Crni vrh observatory at 12th March 2007. Exposure R:120s, V:180s, B:300s.

4 Practical part - data fitting

A fluorescent (emission) iron line in the X-ray band is the strongest line that has been seen in spectrum of many active galactic nuclei and, in particular, in Seyfert type I galaxies. But this line, instead of its narrow origin, appears to be broadened and skewed. This due to the gravitational shifting and relativistic Doppler effect. It can be used as a best well-kept information about properties, geometry and mass flow in the vicinity of central black hole. The broad lines indicates properties like rotation speed accretion disk or its distance from schwarzchild radius. The background will be described now.

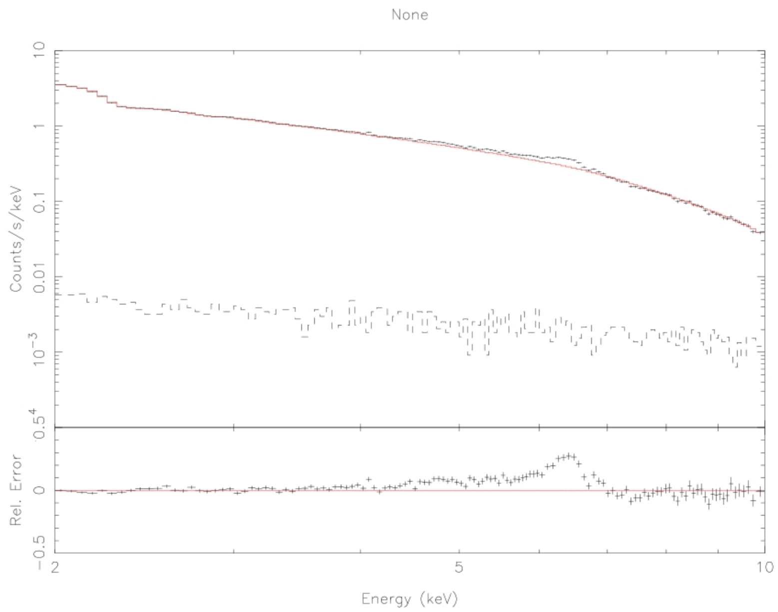


Figure 4: Best fit of MCG-6-30-15; Fe-K line is clearly visible

4.1 Line production

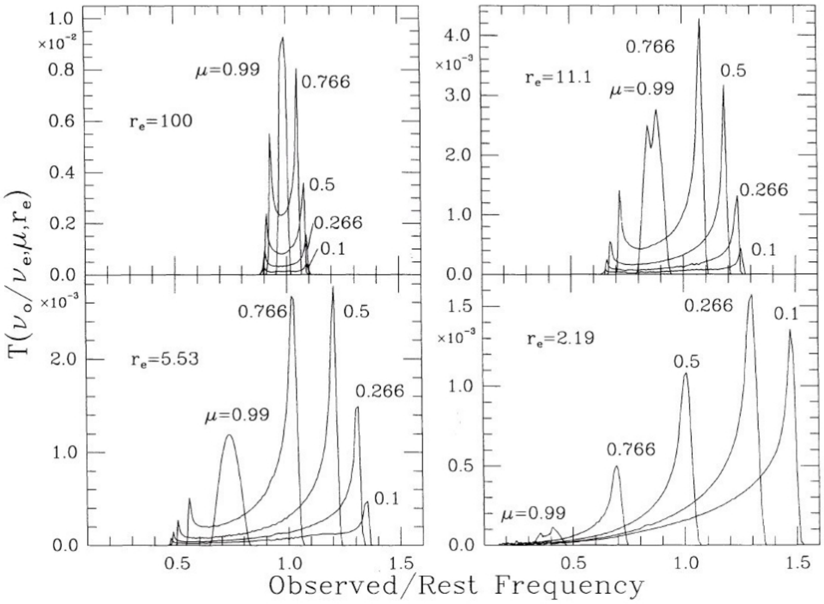
In looking for reason why AGNs emmiting specificaly broadened iron lines, we have to find the answer on questions why AGNs have any power output generaly. It is thought that X-ray light is emmited from accretion processes in the vicinity of black holes. But the main source of the X-ray is not the primary source. Highly ionized gas in accretion disc emmits in optical and UV band. But then is reflected from cold disc parts throught the so called "inverse compton scattering" on which the resulted radiations is in X-ray band. This phenomenon is not peculiar only to supermassive black hole accretions discs, but also to X-ray binaries (when iluminate its stellar companion) or also to solar spectra (when flares in stellar photosphere).

Iluminated "cold" gas in the accretion disc becomes excitated. As in photoelectric absorption, photons excitating heavy atoms where the most favoured in this processes is iron.

4.2 Laor profile

When we started fitting the data, first we fitted whole spectrum, without Fe-K line. We can see result in figure 4.

For fitting Fe-K line we used Laor profile. As you can see in Figure 5 (the inner radius of the accretion disk re is 100 Schwazschild radii) if you observe



an accretion disk from a small angle, near $\phi\,^{\circ}(\mu = cos\ i)$, then the line is only gravitationally redshifted and the emission line is not very distorted. But if you look from a big angle ($\mu \sim 1$; which means you look at the accretion disk edge on) you will see a redshifted horn and a blueshifted horn. The redshifted horn is caused by the part of the accretion disk that is moving away from us, while the blueshifted horn is caused by the part of the accretion disk that is moving toward us. The blue horn of the line is slightly stronger than the red one because of the gravitational boosting. We can see that closer to the black hole the emission lines are even more redshifted and blueshifted because of stronger gravitational field, though the redshifted horn is not visible because of the strong relativistic boosting on the other side of the accretion disk.

When we used Laor profile for our line, we got well fitted Fe-K line (Figure 6).

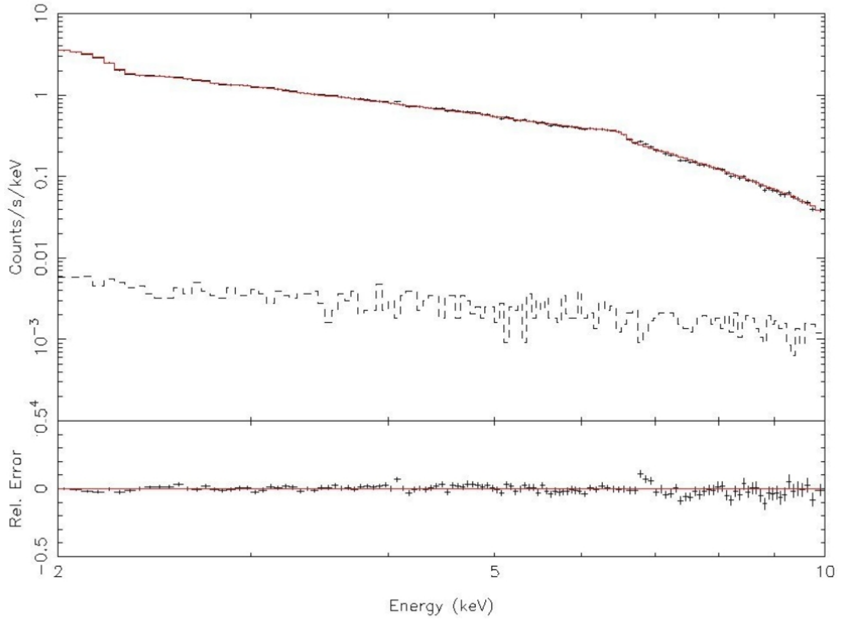
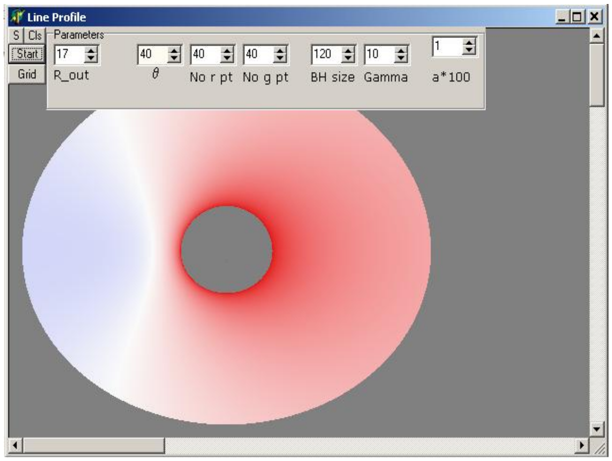


Figure 5: Best fit of MCG-6-30-15; Fe-K line is well fitted

4.3 Comparison of data and prof. Čadež - Calvani model

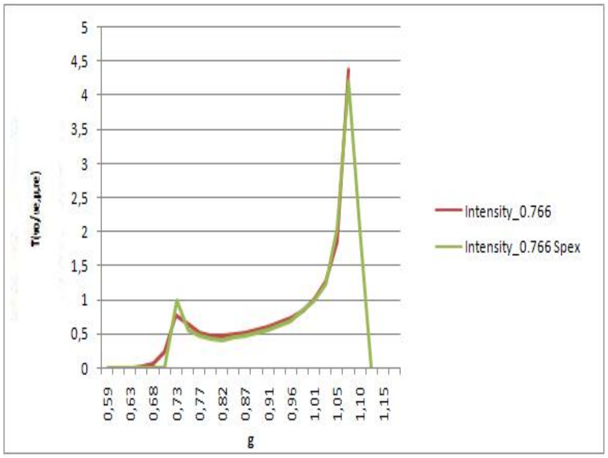
Finishing our Astronomy project, we had one final task. We compared graphs derived with Spex from observational data and graphs modeled by prof. Čadež-Calvani's model. First we entered parameters of the observed black hole: $R_{out} = 17$.

Parameters when we look an angle of observation at 40 degrees in prof. Čadež-Calvani model:

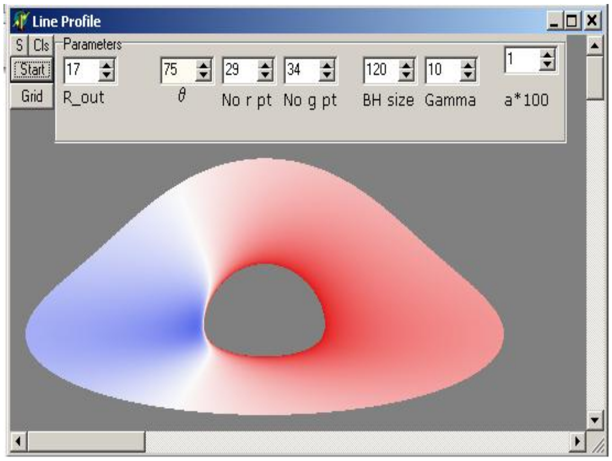


R_out 17
θ 40
No r pt 40
No g pt 40
BH size 120
Gamma 10
a*100 1

Graph when we look an angle of observation at 40 degrees in Spex and prof. Čadež-Calvani model:

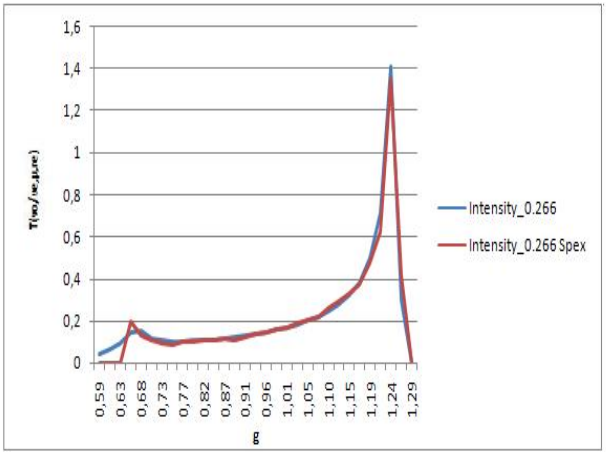


Parameters when we look an angle of observation at 75 degrees in prof. Čadež-Calvani model:

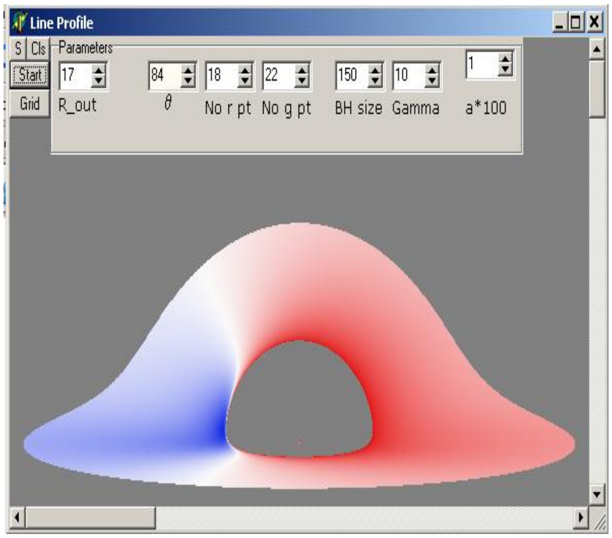


R_out 17
θ 75
No r pt 29
No g pt 34
BH size 120
Gamma 10
a*100 1

Graph when we look an angle of observation at 75 degrees in Spex and prof. Čadež-Calvani model:

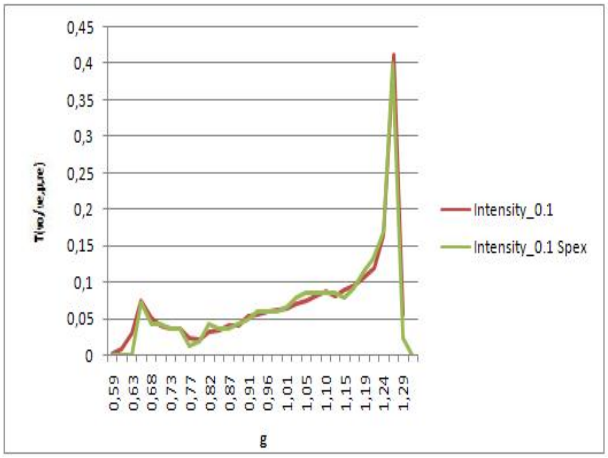


Parameters when we look an angle of observation at 84 degrees in prof. Čadež-Calvani model:

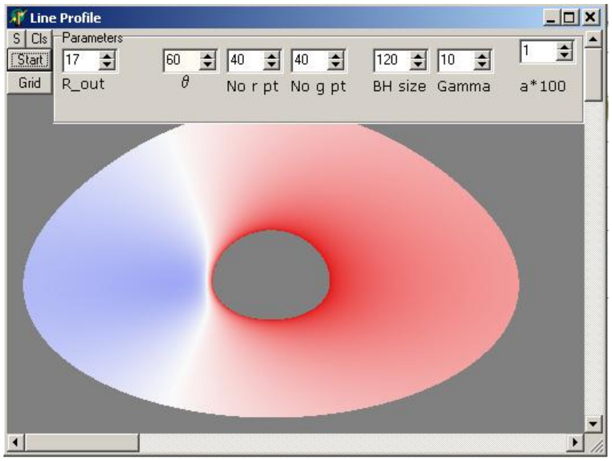


R_out 17
θ 84
No r pt 18
No g pt 22
BH size 150
Gamma 10
a*100 1

Graph when we look an angle of observation at 84 degrees in Spex and prof. Čadež-Calvani model:

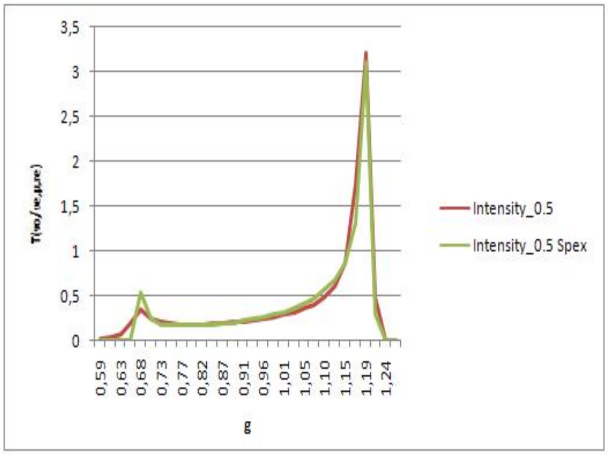


Parameters when we look an angle of observation at 60 degrees in prof. Čadež-Calvani model:

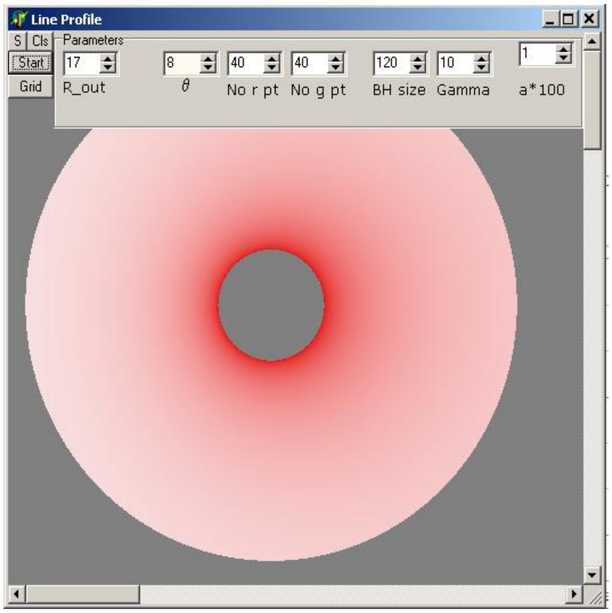


R_out 17
θ 60
No r pt 40
No g pt 40
BH size 120
Gamma 10
a*100 1

Graph when we look an angle of observation at 60 degrees in Spex and prof. Čadež-Calvani model:



Parameters when we look an angle of observation at 8 degrees in prof. Čadež-Calvani model:



R_out 17

θ 8

No r pt 40

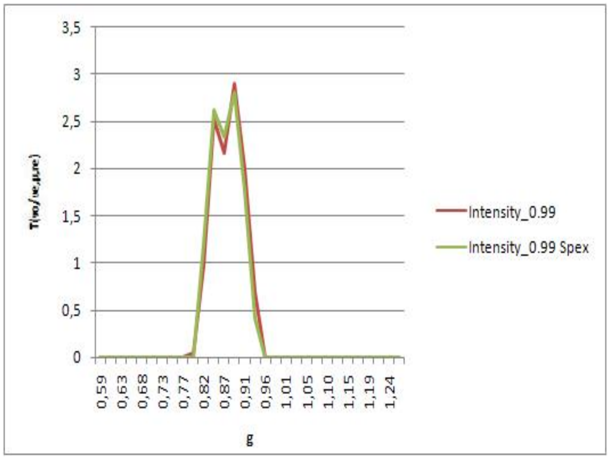
No g pt 40

BH size 120

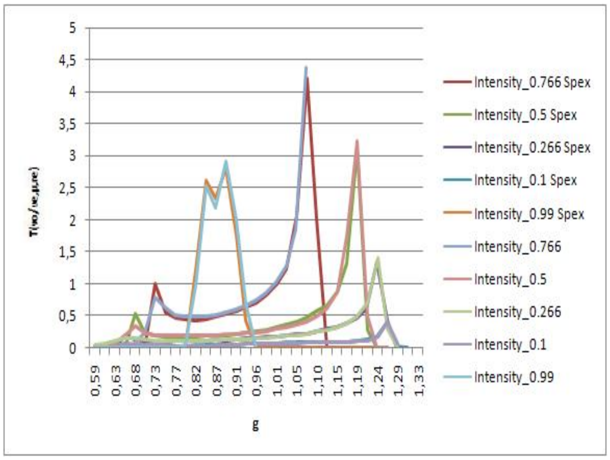
Gamma 10

a*100 1

Graph when we look an angle of observation at 8 degrees in Spex and prof. Čadež-Calvani model:



We also made one picture with all 10 graphs together. Graph of all observations in Spex and prof. Čadež-Calvani model:



As we can see, graphs from Spex match very well to graphs made with prof. Čadež−Calvani model. Lines would match even more if Spex would have unlimited resolution.

The rescaling was done by taking data from Spex and offsetting g-axis so that extremes from Spex and Čadež−Calvani model match. Once the g offset is set, all data from the Čadež−Calvani model is divided by a constant so graphs match in as close as possible. The constant is derived by dividing Čadež−Calvani model data points by data points from Spex and averaging all constants in to one. Čadež−Calvani model intensity data is then divided by that constant. After this rescaling, the graphs fit well enough.

5 Conclusion

We think that this project supports our assumption, that supermassive black holes reside in centers of active galactic nuclei. We focused first on the theoretical part of *AGNs* and then tried to fit our observational data as best as we could to our models. We fitted data to *Laor* profile and compared data with prof. Čadež-Calvani model. We were also able to observe $NGC3077$ in optical spectra at Črni vrh observatory and retrieve some earlier observations of $M106$ in optical spectra.

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