The role of an accretion disk in AGN variability

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Abstract. Optically thick accretion disks are considered to be important ingredients of luminous AGN. The claim of their existence is well supported by observations and recent years brought some progress in understanding of their dynamics. However, the role of accretion disks in optical/UV/X-ray variability of AGN is not quite clear. Most probably, in short timescales the disk reprocesses the variable X-ray flux but at longer timescales the variations of the disk structure lead directly to optical/UV variations as well as affect, or even create, the X-ray variability pattern. We urgently need a considerable progress in time-dependent disk models to close the gap between the theory and the stream of data coming from the AGN monitoring.

1. Introduction

The broad band spectra of bright AGN clearly show the presence of both hot optically thin plasma, responsible for hard X-ray emission, and the relatively cold plasma, presumably an optically thick accretion disk, dominating the optical/UV emission. The two components interact radiatively, as proved by the presence of the so called X-ray reflection component detected for the first time by Pounds et al. (1990).

The exact geometry of the flow is still under discussion. The arguments for the presence of the cold accretion disk are circumstantial but rather strong. The geometry of the hot material is less constrained and the dissipation processes within this plasma are poorly understood.

Strong variability observed in all spectral bands adds to the complexity of the accretion process since the situation cannot be considered as basically stationary. On the other hand, time dependence gives a direct insight into the dynamics of the flow, particularly into the interaction between the hot plasma and the disk.

2. Accretion flow geometry

Bright AGN show a Big Blue Bump (hereafter BBB) component that dominates the optical/UV emission. In Narrow Line Seyfert 1 galaxies and quasars this component clearly extends to the soft X-ray band. BBB emission clearly comes from an optically thick material, as seen from the presence of the Balmer edge (Kishimoto et al. 2004). There are several arguments in favor of this component being roughly a Keplerian disk: (i) in bright quasars and some NLS1 galaxies the predictions based on the simplest stationary Keplerian black body
disk reasonable represent this component (e.g. Koratkar & Blaes 1999, Soria & Puchnarewicz 2002, Czerny et al. 2004); (ii) broad iron Kα line in several NLS1 galaxies is well described as originating from the matter in Keplerian motion (see Reynolds & Novak 2003 for a review); (iii) Hβ line in several objects shows a disk-like component (see Eracleus, this proceedings) (iv) the spectral shape of BBB in AGN is similar to the soft X-ray emission of many X-ray novae in their soft state where the disk formation must take place since the mass supplied through the inner Lagrange point possesses large angular momentum (v) jet formation indicates a disk-like geometry of the flow.

Power law character of the soft X-ray spectrum in NLS1 and quasars (Czerny & Elvis 1987 and subsequent papers), the change of the spectra slope at the Lyman edge position, and the absence of the Lyman edge itself in quasar spectra (Czerny & Zbyszewska 1991, Blaes et al. 2001) are caused by Comptonization of the disk radiation flux, either in the disk outer layers or in the surrounding hot plasma. The disk in those objects extends most probably down to the marginally stable orbit.

Such a disk seems to be absent in a very inactive nucleus like the center of our galaxy (however, see Nayakshin, Cuadra & Sunyaev 2003 for an opposite view), with its X-ray luminosity reaching now some $10^{36}$ erg s$^{-1}$ cm$^{-2}$ during periods of activity.

In intermediate luminosity objects, like radio-galaxies and normal Seyfert 1 galaxies, the disk most likely exist in the outer part of the flow, at distances of few tens - few hundreds of Schwarzschild radii. The argument comes from interpretation of double profiles of optical lines (see Eracleus, this proceedings) and the presence of relatively narrow iron line (see Reynolds & Nowak 2003).

Therefore, most broadly accepted view now is that the character of the flow is mostly determined by the Eddington ratio. In high Eddington ratio objects accretion proceeds through a cold optically thick disk while in lower Eddington ratio the cold disk evaporates close to a black hole, and below a certain radius, $r_{tr}$, depending on accretion rate, the accretion flow proceeds trough some form of optically thin hot flow. A plausible geometry of the flow is shown in Fig. 1.

Even within this frame, several major open questions remain: (i) whether the Comptonizing plasma responsible for formation of the soft X-ray tail of the BBB component is the also the source of the hard X-ray emission; this is possible if plasma consists of mixture of thermal electrons and non-thermal electrons (ii) whether hard X-ray emission actually mostly comes from the magnetic coronal flares or from a standing shock at the basis of the outflow/jet.

Other flow geometries are also considered (for a review, see e.g. Collin et al. 2001), like quasi-spherical inflow of optically thick bobs (Collin et al. 1996), cold disks extending always down to the marginally stable orbit, with X-rays coming either from coronal flares (Galeev, Rosner & Vaiana 1979) or from the base of a jet (Henri & Pelletier 1991). This last scenario predicts interesting effects due to the general relativity when the black hole is maximally rotating and the jet base is very close to the black hole (Miniutti & Fabian 2004). Without precise modeling, including variability studies, it is not possible to differentiate between these alternatives.
3. Basic local timescales of Keplerian flow

In this section I will summarize the basic timescales characteristic for a Keplerian, geometrically thin and optically thick disk as a function of the distance from the black hole and other parameters. Some of these timescales are considerably model-dependent, as notified.

3.1. Dynamical timescale

If the accretion flow is roughly Keplerian, the dynamical timescale of the matter is given by the Keplerian frequency:

\[ t_{\text{dyn}} = \frac{1}{\Omega_K} = \sqrt{\frac{GM}{r^3}} \]  

(1)

determined by the mass of the black hole, \( M \), and the radius \( r \). This timescale, equal to the orbital period, describes the motion at the circular orbit, the local rotation with the epicyclic frequency (for example, if a magnetic loop emerges from the disk surface, its foots entangle in this timescale), the dynamical oscillations in the direction perpendicular to the disk surface, the timescale to achieve the hydrostatic equilibrium in the disk and the sound crossing timescale in the disk, in the vertical direction. The free fall timescale from the radius \( r \) towards the black hole is also of the same order of magnitude.

Very close to a black hole, the Keplerian frequency, the epicyclic frequency and the oscillations in the vertical direction differs due to the effects of General Relativity (see e.g. Kato 2001). At distances larger than 10 \( R_{\text{Schw}} \) we can neglect these effects.

We can conveniently express the dynamical timescale using \( R_3 = r/(3R_{\text{Schw}}) \) as dimensionless units of radius and \( M_8 = M/(10^8 M_\odot) \) as dimensionless units of mass

\[ t_{\text{dyn}} = 10^4 R_3^{3/2} M_8 \quad [\text{s}]. \]  

(2)
The timescale of propagation of the sound waves in the radial direction, $t_{\text{sound}-r}$ is longer

$$t_{\text{sound}-r} = t_{\text{dyn}} \left( \frac{r}{h_d} \right),$$  \hspace{1cm} (3)

where $h_d$ is the disk thickness.

### 3.2. Thermal timescale

Thermal timescale of the disk can be determined if the heating and cooling mechanisms are specified since this timescale is defined as a ratio of internal energy to the cooling or heating rate. Here we adopt the assumption that the disk viscosity is described by the parameter $\alpha$ introduced by Shakura & Sunyaev (1973). The support for this idea is discussed in more detail in Sect. 5.1. If the assumption that the stress tensor is equal to $\alpha P$ is introduced, where $P$ is the total pressure, the characteristic thermal timescale of the disk is given by

$$t_{\text{th}} = \alpha^{-1} t_{\text{dyn}}.$$  \hspace{1cm} (4)

This timescale does not depend on the optical depth of the disk or the cooling mechanism so we have the same thermal timescale for a cold optically thick disk and a hot optically thin flow. Assuming $\alpha = 0.1$ as characteristic value of the viscosity parameter, we obtain

$$t_{\text{th}} = 10^5 \alpha_{0.1}^{-1} R_3^{3/2} M_8 \text{ [s].}$$  \hspace{1cm} (5)

### 3.3. Viscous timescale

Viscous timescale is defined as a characteristic timescale of mass flow, i.e. locally as the ratio of the radius to the radial velocity. If we assume the $\alpha$ disk model, we can obtain the following, more convenient expression

$$t_{\text{visc}} = t_{\text{th}} \left( \frac{r}{h_d} \right)^2.$$  \hspace{1cm} (6)

For a cold optically thick disk, the $h_d/r$ ratio is small so the viscous timescale is orders of magnitude longer than the thermal timescale. Even if the Eddington ratio of an object is close to 1, this ratio remains relatively small above $\sim 10 R_{\text{Schw}}$. However, for highly super-Eddington flow or for a hot optically thin plasma at virial temperature $h_d/r$ ratio is close to 1 and the viscous timescale of such a flow is equal to the thermal timescale. Adopting $h_d/r = 0.1$ as a characteristic value, we can write

$$t_{\text{visc}} = 10^7 \alpha_{0.1}^{-1} \left( \frac{r}{10h_d} \right)^2 R_3^{3/2} M_8 \text{ [s].}$$  \hspace{1cm} (7)

Actually, the disk thickness depends is roughly given by $h_d = 10 \dot{m}$, in the inner, radiation pressure dominated region, and depends both on the accretion rate and the disk radius further out. Estimates are influenced by the description of the disk opacity. Examples of numerical results are shown in Fig. 2 computed using the disk structure code of Różańska et al. (1999).
3.4. Timescales of X-ray reprocessing

Variations in the X-ray flux, generated either in the magnetic loops above the disk or in the innermost part of the flow, leads to changes of the condition in the disk surface layers. The timescales of the processes involved can be estimate as functions of the local number density, $n$, temperature, $T$, disk radiation flux, $F_{\text{soft}}$, and the cooling function, $\Lambda$, in the disk surface layers, as discussed by Collin et al. (2003). Introducing the dimensionless parameters we obtain the following estimates. The characteristic timescale for the radiation transfer is

$$t_{\text{rt}} = \frac{\tau_{\text{es}}(\tau_{\text{es}} + 1)}{\sigma_Tcn} \approx 100n_{12}^{-1} \text{ [s]},$$

The ionization state of the disc surface adjusts on a timescale

$$t_{\text{ion}} = \frac{h\nu}{F_X\sigma_{\text{ion}}} \approx 10^{-7}F_{16} \text{ [s]}$$

and recombination proceeds in the timescale

$$t_{\text{rec}} = \frac{1}{n\alpha_{\text{rec}}} \approx 10n_{12}^{-1} \text{ [s]}. \tag{10}$$

The thermal timescale of the disk surface layers depends on the ionization state and, consequently, on the cooling mechanism. If the ionization is weak or mod-
erate, atomic cooling dominates and the timescale of restoring the thermal equilibrium is given by

\[ t_{\text{th-surface}}^{\text{atomic}} = \frac{n k T}{n^2 \Lambda} \approx 10 T_6 n_{12}^{-1} \Lambda_{23}^{-1} \text{[s]} \tag{11} \]

while in the case of very strong ionization the Compton cooling dominates (the temperature of the disk surface is in this case close to the Compton temperature) and the timescale is

\[ t_{\text{th-surface}}^{\text{Compton}} = \frac{n k T}{F_{\text{soft}} F_{\text{mc}} \sigma T n} \approx 10^4 F_{14}^{-1} \text{[s]}. \tag{12} \]

Heating of the disk surface affects the hydrostatic equilibrium and the characteristic timescale for expansion or contraction of the disk surface layers is given by

\[ t_{\text{dyn-surface}} = \frac{H}{c_s} \approx 10^5 T_6^{-1/2} n_{12}^{-1} \text{[s]}. \tag{13} \]

We see that these timescales are generally very short, apart from the last one which may be comparable, or longer than the dynamical timescale of the disk body.

### 3.5. Timescale of cold disk removal

If accretion flow proceeds as shown in Fig. 1 and the transition radius changes with time, we need an estimate of the characteristic timescale of the removal of the cold disk from a given radius down. This removal can happen either in a form of evaporation and a change of accretion flow into an optically thin flow, or in a form of ejection (outflow). In both cases we require the change of the disk temperature to roughly the virial temperature and we need to accumulate enough energy from the accretion flow for the transition to happen. Assuming the \( \alpha \) viscosity disk model, we obtain

\[ t_{\text{evap}} = \frac{E}{\eta M c^2} = \frac{k}{\alpha H P \Omega_K} \equiv \tau_{\text{visc}}, \tag{14} \]

so the timescale is the same at the cold disk viscous timescale at a given radius. We can also obtain more general estimate, without assuming \( \alpha \) disk.

\[ t_{\text{evap}} = \frac{E}{\eta M c^2}; \quad E = \pi r^2 \Sigma \frac{k}{m_H} T_v; \quad \eta = \frac{r}{4 R_{\text{Schw}}}, \tag{15} \]

which can be expressed conveniently as

\[ t_{\text{evap}} = 1000 \left(\frac{r}{100 R_{\text{Schw}}}\right)^2 \dot{m}_{0.1} M_8 \text{ [yr]}. \tag{16} \]

The process is therefore long; observations show that in galactic sources state transitions, believed to be due to the cold disk removal, last one day, and in AGN they should take thousands of years.

Therefore, if the inner disk seems to disappear in a timescale of months – years, we should rather interpret it as temporary suppression of the disk emission, either due to the excessive cooling or due to suppression of the energy dissipation, e.g. turning off the MRI instability by temporary formation of strong ordered magnetic field (see Marsher, this proceedings).
4. Basic non-local aspects

The local state of the plasma, at any radius, is affected by the processes taking place elsewhere. The influence propagates both in → out and out → in.

The first class includes (i) irradiation of the outer disk by the radiation generated in the inner part (either direct or indirect, through the scattering of some part of emission in the optically thin plasma present in the inner region) (ii) mechanical transport of energy in the form of convection in the optically thin flow (e.g. CDAF models of Narayan, Igumenshchev & Abramowicz 2000), or wind/coronal outflow with large angular momentum (e.g. Cao & Spruit 1994; Janiuk & Czerny 2004). Irradiation, or any kind of additional energy transport, significantly complicates the use of the timescales discussed in Sect. 3.

In the case of strongly irradiated disk, the emission at a given wavelength comes predominantly from much larger radius than predicted by the model without irradiation, and the observed variability may contain both the contribution from the variable irradiation and the intrinsic variability of the disk.

The second class includes (i) modulations of accretion rate (ii) coronal inflow. The first effect may be caused by external perturbations of the flow but certain class of modulations is predicted to develop internally (see Sect. 5). The second effect may be present if significant angular momentum transfer can take place in the disk corona itself. Since the viscous timescale in a hot corona may be comparable to its thermal timescale such surface inflow may proceed much faster than the inflow through the disk main body.

5. Theory of disk instabilities

Disk instabilities do not necessarily destroy the accretion disk, as sometimes believed. In opposite, they seem to provide the explanation for some aspects of the accretion disk existence and behaviour.

5.1. Magnetorotational instability

This instability is now established as the physical mechanism of the accretion disk viscosity (Balbus & Hawley 1991). Advanced MHD computations show that this instability roughly corresponds to $\alpha \sim 0.1$ in gas pressure dominated flow (Hawley & Krolik 2001). However, besides providing the time and spatially averaged effective viscosity, the instability produces (i) local fluctuations in dissipation and the accretion rate (ii) certain level of disk clumpiness (iii) specific vertical stratification of the dissipation.

The first effect is now considered as an attractive qualitative explanation of the power law type shape of the power spectra in X-ray energy band in objects like galactic sources in soft state and AGN with the same shape of power spectra (Lyubarskij 1997, King et al. 2004). The second effect may provide the explanation for the apparent variable clumpiness of the disk requested to explain the variations of the emission line profiles (Asatrian, this proceedings; Eracleus, this proceedings; Sergeev, this proceedings, Shapovalova, this proceedings). The third effect leads in a natural way to formation of either strong magnetic flares above the disk body, or magnetically heated upper disk skin of moderate optical depth. The first result was obtained when the cooling was neglected in MHD
simulations (Miller & Stone 2000) while the second one was obtained for a radiation pressure dominated medium with flux-limited approximation for cooling (Turner 2004). The issue will be resolved when MHD simulations are performed with Compton cooling included.

MHD simulations of Miller & Stone also show that large loop formation takes more than one dynamical timescale so the timescale of the corona formation may be between the dynamical timescale and the thermal timescale of the disk body.

5.2. Radiation pressure instability

Standard $\alpha$ disk models are unstable if dominated by radiation pressure (Pringle, Rees & Pachoiczyk 1973). AGN disk models show the domination by radiation pressure for a broad range of Eddington rates. Disk evaporation is not likely to prevent the existence of such a disk region (e.g. Różańska & Czerny 2000). Computations of disk time evolution under the influence of such instability show semi-regular outbursts in viscous timescale of the inner $\sim 100R_{\text{Schw}}$ (Szuszkiewicz & Miller 1998, Teresi, Molteni & Toscano 2004; see also Janiuk, Czerny & Siemiginowska 2000 in the context of GRS 1915+105). Such effect is seen only in one galactic source, GRS 1915+105, which most probably has the highest Eddington rate (Done, Wardziński & Gierliński 2004), but neither in other galactic sources nor in AGN. Scaling GRS 1915+105 outbursts, lasting 100 - 1000 s to black hole mass $10^7M_\odot$ we would expect outbursts lasting $3\text{ yr} - 30\text{ yr}$.

The redistribution of the dissipation in the vertical direction due to MRI instability and magnetic energy transport may suppress this instability (e.g. Czerny et al. 2003). MHD simulations by Turner (2004) mentioned in Sect. 5.1 indicate that the instability is not completely dumped out but partially suppressed: instead of large outbursts we should expect rather irregular variability by a factor of a few, roughly in thermal timescale.

5.3. Ionization instability

Present in outer parts of the disk in galactic sources (X-ray novae and dwarf novae; for a review, see Lasota 2001). It remains an open question whether the mechanism applies to AGN. In any case, expected timescale are thousands to millions of years (e.g. Janiuk et al. 2004).

6. Time-dependent disk models

Most of the work was devoted so far to the stationary disk models and to proper modelling of their spectra. A few existing models were aimed at studying some specific effects.

Global evolution of accretion disks under the radiation pressure instability was studied by Honma, Matsumoto & Kato (1991), Szuszkiewicz & Miller (1998), Nayakshin, Rappaport & Melia (2000), Szuszkiewicz & Miller (2001), Janiuk et al. (2002), Teresi, Molteni & Toscano (2004).

Global evolution of AGN disks under ionization instability was calculated by Mineshige & Shields (1990), Siemiginowska, Czerny & Kostyumin (1996),
7. The origin of observed optical/UV variability

Practically all radio quiet AGN show some variability in the optical/UV band. This variability may be due to (i) variable X-ray irradiation, (ii) intrinsic disk variability caused by disk instabilities, (iii) variable obscuration. It is most probable that more than one mechanism is in action. An idea of separate slow and fast variability was advertised by Lyutyi (this proceedings) and de Vries (this proceedings). Similarly, the comparison of the power spectra in the optical and X-ray band indicate that at shorter timescales the optical variations are caused by irradiation but at longer timescales of years there seems to be an excess of the optical variations (Czerny et al. 1999, Czerny et al. 2003b).

7.1. variable X-ray irradiation

Results of many monitoring projects, with good coverage of short timescale variability, have been discussed during this conference. Observations of Seyfert galaxies in the optical band show relative delays of continuum emission in various wavelengths by a day or a few days. The results are roughly consistent with variable X-ray irradiation (Sergeev, this proceedings). Similar conclusion was reached for IR monitoring, and the delays with respect to the optical emission were naturally longer (Oknyanskij, this proceedings). In this case the role of the disk is mostly passive in this sense that character of the variability is determined by the intrinsic timescales of the X-ray emitting plasma plus the light travel time.

Quasars are also variable in the optical band when monitored for several years (see Papadakis & Magotis; Hawkins; de Vries, this proceedings). Delays were not determined so far so we have less direct constraints of the variability mechanism. In quasars the X-ray emission is relatively less important than in Seyfert 1 galaxies so we might expect relatively larger role of the intrinsic disk variability.

As for the theory of disk irradiation, there has been a considerable progress in modeling of the X-ray reprocessing, including the stratification of the disk surface layers (e.g. Goosmann, this proceedings). New models start to pay attention to the time-dependent response of the disk surface layers (e.g. Nayakshin & Kazanas 2002, Collin et al. 2003, Czerny & Goosmann 2004). Also the angular-dependent emissivity of the hot material should be studied. Poor correlation between primary X-ray emission and X-ray reflection is frequently seen in the data. For example, optical events without an X-ray counterpart were observed in Akn 564 which may mean that the hot plasma emission may be strongly anisotropic (see Gaskell, this proceedings).
7.2. intrinsic variations in disk dissipation

However, when a combined X-ray and UV monitoring is performed, a more complicated picture emerges (Uttley, this proceedings; Arevalo, this proceedings). We certainly see some reprocessing in shorter timescales but at somewhat longer timescales we have an additional effect of optical emission leading X-ray variability. Not many such examples are known because of the difficulties in the proper data coverage. The optical variations leading by a few days detected in NGC 4051 ($M = 5 \times 10^5 M_\odot$) would correspond to timescales of a few hundred days for NGC 5548 or NGC 4151. The presence of such delays indicate that changes in the disk interior lead to changes in the disk emission and subsequent changes in the state of the hot material. The candidates for the prime cause of those variations are either MRI turbulence, or strongly suppressed radiation pressure instability, as in simulations of Turner (2004). The local effective timescale is in this case not far from the thermal timescale. This possibility was explored by Starling et al. (2004). They interpreted the optical/UV variability in a sample of PG quasars as happening in local thermal timescale and determined the value of the viscosity parameter. Obtained value, $\alpha \sim 0.02$ is reasonable. However, other interpretations of quasar variability are still open.

7.3. Intrinsic variability vs. variable obscuration as the cause of large variations

Many AGN show occasional dramatic changes in their properties, including the change in their classification (e.g. from LINER to Seyfert, Yuan et al. 2004; Seyfert class change, e.g. Lyutyi, this proceedings; switch off the X-ray source, e.g. Guainazzi et al. 1998). Monitoring brings more and more of such examples. Therefore, one of the big questions discussed during this conference was: are these changes intrinsic or do they result from variable obscuration?

The success of the reverberation approach to the analysis of the BLR (Peterson, this proceedings) shows that strong intrinsic variability is certainly present. Also hints for asymmetry of the variability (rise time frequently shorter than the decay time; see Lyutyi, this proceedings; Hawkins, this proceedings) supports the intrinsic character of the luminosity variations. However, it does not necessarily mean that variable obscuration is absent.

Statistical studies show that highly obscured AGN are four times more numerous than unobscured (e.g. Treister et al. 2004). Obscuration is most probably very important also in apparently unobscured objects like NLS1 (e.g. Constantin and Shields 2003) or quasars (e.g. Czerny & Li 2004). Variable obscuration in single objects was claimed to be seen in a number of sources (Risaliti et al. 2002), and partial covering was successfully applied e.g. to NLS1 IRAS 13224-3809 by Boller et al. (2003). Also interestingly, 9 year observations of NGC 4151 with BATSE in $\gamma$-ray band show variability (Hill et al. 2004) but does not seem to follow the 10-year timescale of outburst seen in this source between 1991 and 2000. It might mean that slow variability, strongly seen in optical/UV and less in X-ray band is mostly due to variable extinction. Strongly variable extinction is also an important feature of a class of galactic sources known as dippers (e.g. 'Big Dipper'; Smale et al. 2001).

Therefore, we possibly have a variable extinction as well, perhaps resulting from the changes in gas ionization and dust evaporation or sublimation.
8. Summary

Cold, geometrically thin, optically thick accretion disk certainly plays a role in the AGN variability. It reprocesses the variable X-ray emission of the coexisting hot, optically thin plasma in a complex way, thus playing mostly a passive role in the variability at the shortest timescales. There are arguments, however, supporting the idea of an active role of the disk at longer timescales, and the internal disk variability may be possibly connected with the MRI instability and/or partially saturated radiation pressure instability. These changes, in turn, may propagate within the disk and affect the hot X-ray emitting plasma. Determination of the nature of the optical/UV variations need not only further monitoring, but also a development of the time-dependent disk models, including the non-local phenomena. The description of X-ray reprocessing is already quite advanced but the reasonable description of time-dependent flow is still missing. MHD simulations have poor description of cooling and cannot be extended to timescales comparable to the viscous timescale for technical reasons, while simpler models based on $\alpha$ prescription still miss important ingredients like better approximation of the vertical stratification of the dissipation and the role of the magnetic field in energy transport.

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