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The Role of the Accretion Disk in AGN Variability

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Abstract. Optically-thick accretion disks are considered to be important ingredients of luminous AGNs. Evidence for their existence is well supported by observations and in recent years there has been some progress in understanding their dynamics. However, the role of accretion disks in optical/UV/X-ray variability of AGNs is not quite clear. Probably, on short timescales, the disk reprocesses the variable X-ray flux, but, on longer timescales the variations of the disk structure lead directly to optical/UV variations as well as affecting, or even creating, the X-ray variability pattern. Considerable progress is urgently needed in modelling time-dependent disk to close the gap between theory and the stream of data coming from AGN monitoring.

1. Introduction

The broad-band spectra of bright AGNs clearly show the presence of both a hot, optically-thin plasma, responsible for hard X-ray emission, and a 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 AGNs 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 optically-thick material, as shown by the detection of the Balmer edge in polarized flux (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) the broad Fe $K\alpha$ line in several NLS1 galaxies is well described as originating from the matter in Keplerian motion (see Reynolds & Novak 2003 for a review); (iii) $H\beta$ line in several objects shows a disk-like component (see Eracleous, these proceedings); (iv) the spectral shape of the BBB in AGNs is similar to the soft X-ray emission of many X-ray novae in their soft state where disk formation must take place since the mass supplied through the inner Lagrange point possesses large angular momentum; and (v) jet formation indicates a disk-like geometry of the flow.

The 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 outer layers of the disk outer, or in the surrounding hot plasma. The disk in those objects most probably extends down to the last 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 opposing 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 exists in the outer part of the flow, at distances of a few tens to a few hundreds of Schwarzschild radii. The argument comes from interpretation of double profiles of optical lines (see Eracleus, these proceedings) and the presence of a relatively narrow Fe Kα line (see Reynolds & Nowak 2003).

Given the above, the 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 objects, the cold disk evaporates close to a black hole, and below a certain radius, r_{tr}, depending on the accretion rate, the accretion flow proceeds through some form of optically-thin hot flow. A plausible geometry of the flow is shown in Fig. 1.

Even within this framework, 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; and (ii) whether hard X-ray emission actually mostly comes from magnetic coronal flares or from a standing shock at the basis of the outflow/jet.

Other flow geometries are also considered (see, e.g., Collin et al. 2001), like quasi-spherical inflow of optically-thick bobs (Collin et al. 1996). 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 characteristic timescales characteristic for a Keplerian, geometrically-thin and optically-thick disk as a function of the

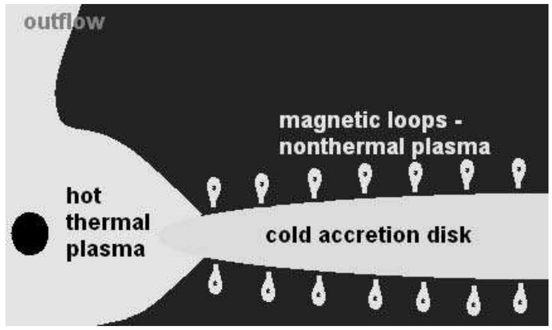

Figure 1. Schematic view of an accretion flow: cold disk with magnetic flares above it in outer region, replaced with the hot, optically-thin accreting plasma in the inner region, and an accompanying outflow. The transition radius is expected to decrease with increasing accretion rate.

distance from the black hole and other parameters. Some of these timescales are considerably model-dependent, as will be pointed out.

3.1. The Dynamical Timescale

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

$$t_{dyn} = \Omega_K^{-1} = \sqrt{\frac{GM}{r^3}} \tag{1}$$

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 feet entangle on 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_{Schw} we can neglect these effects.

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

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

The timescale of propagation of the sound waves in the radial direction, $t_{sound-r}$ is longer

$$t_{sound-r} = t_{dyn}(\frac{r}{h_d}), \tag{3}$$

where h_d is the disk thickness.

3.2. The Thermal Timescale

The 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 α 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 αP is introduced, where P is the total pressure, the characteristic thermal timescale of the disk is given by

$$t_{th} = \alpha^{-1} t_{dyn}. \tag{4}$$

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

$$t_{th} = 10^5 \alpha_{0.1}^{-1} R_3^{3/2} M_8 \quad [\mathrm{s}]. \tag{5}$$

3.3. The Viscous Timescale

The viscous timescale is defined as the characteristic timescale of mass flow, i.e., locally, as the ratio of the radius to the radial velocity. If we assume the α disk model, we can obtain the following, convenient expression

$$t_{visc} = t_{th} (\frac{r}{h_d})^2. \tag{6}$$

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 $\sim 10 R_{Schw}$. However, for highly super-Eddington flow, or for a hot, optically-thin plasma at the virial temperature the ratio h_d/r 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

$$t_{visc} = 10^7 \alpha_{0.1}^{-1} (\frac{r}{10 h_d})^2 R_3^{3/2} M_8 \quad [\mathrm{s}]. \tag{7}$$

Actually, the disk thickness dependency is roughly given by $h_d = 10\dot{m}$ in the inner, radiation-pressure-dominated region. Further out it depends both on the accretion rate and the disk radius. Estimates of the thickness 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, lead to changes of the condition in the surface layers of the disk. The timescales of the processes involved can be estimated as functions of the local number density, n, temperature, T, disk radiation flux, F_{soft}, and the cooling function, Λ, in the disk surface layers, as

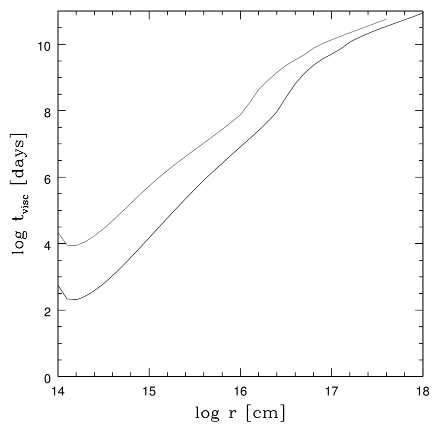

Figure 2. The local viscous timescale of an accretion disk around $10^8 M_{odot}$ black hole for an Eddington ratio of 0.3 (lower curve) and 0.03 (upper curve), and viscosity parameter $\alpha = 0.02$

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discussed by Collin et al. (2003). Introducing the dimensionless parameters we obtain the following estimates. The characteristic timescale for the radiation transfer is

$$t_{rt} = \frac{\tau_{es}(\tau_{es}+1)}{\sigma_T c n} \approx 100 n_{12}^{-1} \quad [\mathrm{s}], \tag{8}$$

the ionization state of the disk surface adjusts on a timescale

$$t_{ion} = \frac{h\nu}{F_X \sigma_{ion}} \approx 10^{-7} F_{16} \quad [\mathrm{s}] \tag{9}$$

and recombination proceeds on a timescale

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

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 moderate, atomic cooling dominates and the thermal equilibrium restoration timescale is given by

$$t_{th-surface}^{atomic} = \frac{nkT}{n^2\Lambda} \approx 10 T_6 n_{12}^{-1} \Lambda_{23}^{-1} \quad [\mathrm{s}] \tag{11}$$

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

$$t^{Compton}_{th-surface} = \frac{nkT}{F_{soft}\frac{4kT}{m_e c^2}\sigma_T n} \approx 10^4 F_{14}^{-1} \quad [\mathrm{s}]. \tag{12}$$

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

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

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 material inside a given radius. 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 set the change of the disk temperature to be roughly the virial temperature, and we need to accumulate enough energy from the accretion flow for the transition to happen. Assuming the α viscosity disk model, we obtain

$$t_{evap} = \frac{E}{F} = \frac{\frac{k}{m_H}\Sigma T_v}{\alpha H P \Omega_K} \equiv \tau_{visc}, \tag{14}$$

so the timescale is the same as the cold disk viscous timescale at a given radius. We can also obtain more general estimate, without assuming α disk.

$$t_{evap} = \frac{E}{\eta \dot{M} c^2}; \qquad E = \pi r^2 \Sigma \frac{k}{m_H} T_v; \qquad \eta = \frac{r}{4R_{Schw}}, \tag{15}$$

which can be expressed conveniently as

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

The process of cold disk removal is therefore long. Observations show that in X-ray binaries transitions, believed to be due to the cold disk removal, take one day; in AGN they should take thousands of years.

Therefore, if the inner disk seems to disappear in a timescale of months or 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 of the magnetorotational instability by temporary formation of strong ordered magnetic field (see Marscher, these 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 case (in → out) 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 the emission in the optically-thin plasma present in the inner region) (ii) mechanical transport of energy by 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 a strongly irradiated disk, the emission at a given wavelength comes predominantly from a much larger radius than predicted by a 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 case (out → in) includes (i) modulations of accretion rate (ii) coronal inflow. The first effect may be caused by external perturbations of the flow, but certain types of modulations are predicted to develop internally (see Sect. 5.1.. 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 of the order of its thermal timescale such surface inflow may proceed much faster than inflow through the disk main body.

5. Theory of Disk Instabilities

Disk instabilities do not need to destroy the accretion disk, as is sometimes believed. On the contrary, they seem to provide the explanation for some aspects of the accretion disk existence and behavior.

5.1. Magneto-Rotational Instability (MRI)

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, on the top of the time- and spatially-averaged effective viscosity, the instability produces (i) local fluctuations in dissipation and accretion rate, (ii) a certain level of disk clumpiness, and (iii) specific vertical stratification of the dissipation.

Local fluctuations in dissipation and accretion rate are 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 their soft state and AGN with the same shape of power spectra (Lyubarskij 1997, King et al. 2004). The MRI instability may provide the explanation for the apparent variable clumpiness of the disk requested to explain the variations of the emission line profiles (see the contributions by Asatrian, Eracleus, Sergeev, and Shapovalova, in these proceedings). The third effect (specific vertical stratification of the dissipation) leads in a natural way to the formation of either strong magnetic flares above the disk body, or a 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 (2000) also show that large loop formation takes more than one dynamical timescale so the timescale of corona formation may be between the dynamical timescale and the thermal timescale of the disk body.

5.2. Radiation-Pressure Instability

Standard α disk models are unstable if dominated by radiation pressure (Pringle, Rees & Pacholczyk 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 the temporal evolution of a disk under the influence of such instabilities show semi-regular outbursts in viscous timescale of the inner $\sim 100 R_{Schw}$ (Szuszkiewicz & Miller 1998, Teresi, Molteni & Toscano 2004; see also Janiuk, Czerny & Siemiginowska 2000 in the context of GRS 1915+105). Such an effect is seen only in one Galactic source, GRS 1915+105, which most probably has the highest Eddington rate (Done, Wardziński & Gierliński 2004), but not in other Galactic sources or in AGNs. Scaling GRS 1915+105 outbursts, lasting 100 - 1000 s, to a black hole mass of $10^7 M_\odot$, we would expect outbursts lasting 3 yr - 30 yr.

The redistribution of the dissipation in the vertical direction due to the MRI instability and magnetic energy transport, however, may suppress the radiation-pressure instability (e.g., Czerny et al. 2003). MHD simulations by Turner (2004) mentioned in Sect. 5.1. indicate that instead of large outbursts we see rather irregular variability by a factor of a few.

5.3. Ionization Instability

The ionization instability is present in the 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. Intrinsic Variability vs. Variable Obscuration

Many AGNs 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, these proceedings; switching off of the X-ray source, e.g., Guainazzi et al. 1998). Monitoring brings up more and more such examples. Therefore, one of the big questions discussed during this conference was: are these changes intrinsic, or do they result from variable obscuration?

Statistical studies show that highly-obscured AGNs are four times more numerous than unobscured AGNs (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 et al. 2004).

Variable obscuration in individual sources has been claimed to be seen in a number of objects (Risaliti et al. 2002).

The success of the reverberation approach in the analysis of the BLR (Peterson, these proceedings) shows that strong intrinsic variability is certainly present. Also, hints for asymmetry of the variability (rise time frequently shorter that the decay time; see papers by Lyutyi and Hawkins in these proceedings) support the intrinsic character of the luminosity variations. However, we possibly have variable extinction as well, perhaps resulting from the changes in gas ionization and dust evaporation or sublimation.

7. The Origin of Optical/UV Variability

Results of many monitoring projects have been discussed during this conference. Observations of Seyfert galaxies in the optical band show relative delays of continuum emission in various wavelengths by one or more days. The results are roughly consistent with variable irradiation (Sergeev, these proceedings). Similar conclusion was reached for IR monitoring, but the delays with respect to the optical emission were naturally longer (Oknyanskij, these proceedings).

When combined X-ray and UV monitoring is performed, however, a more complicated picture emerges (Uttley, these proceedings; Arevalo, these proceedings). We certainly see some reprocessing in shorter timescales but at longer timescales we have an additional effect of optical emission *leading* X-ray variability. Therefore, an idea of separate slow and fast variability advertised by Lyutyi (these proceedings) and de Vries (these proceedings) sounds attractive. Optical variations leading by a few days 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. Additionally, X-ray events without an optical counterpart were observed in Akn 564 (see Gaskell, these proceedings). Also, a comparison of the power spectra in the optical and X-ray bands on timescales of years seem to indicate the domination of the optical variations (Czerny et al. 2003b).

Quasars are also variable in the optical band when monitored for several years (see Papadakis & Magotis; Hawkins; de Vries, these proceedings). Wavelength-dependent delays have not been determined so far, so we have even less direct constraints. In quasars the X-ray emission is relatively less important than in Seyfert 1 galaxies so we might expect a larger role of the intrinsic disk variability. Starling et al. (2004) interpreted the optical/UV variability in a sample of PG quasars as occurring on a local thermal timescale and determined a value of the viscosity parameter. The value they obtained, $\alpha \sim 0.02$ is reasonable. However, other possibilities are still open.

Determination of the nature of the optical/UV variations needs not only further monitoring, but also a development of the time-dependent disk models, including the non-local phenomena. So far, there has been a considerable progress in modelling of X-ray reprocessing, including the stratification of the disk surface layers (e.g., Goosmann, these proceedings). However, a 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 an

α prescription still miss important ingredients like better approximation of the vertical stratification of the dissipation.

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