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The Observational Appearance of Slim Accretion Disks

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Abstract

We reexamine the hypothesis that the optical/UV/soft X-ray continuum of Active Galactic Nuclei is thermal emission from an accretion disk. Previous studies have shown that fitting the spectra with the standard, optically thick and geometrically thin accretion disk models often led to luminosities which contradict the basic assumptions adopted in the standard model. There is no known reason why the accretion rates in AGN should not be larger than the thin disk limit. In fact, more general, slim accretion disk models are self-consistent even for moderately super-Eddington luminosities. We calculate here spectra from a set of thin and slim, optically thick accretion disks, assuming for simplicity a modified black body local emission with no relativistic corrections. We discuss the differences between the thin and slim disk models, stressing the implications of these differences for the interpretation of the observed properties of AGN. We found that the spectra can be fitted not only by models with a high mass and a low accretion rate (as in the case of thin disk fitting) but also by models with a low mass and a high accretion rate. In the first case fitting the observed spectra in various redshift categories gives black hole masses around 10^9 $M_\odot$ for a wide range of redshifts, and for accretion rates ranging from 0.4 (low redshift) to 8 $M_\odot$/year (high redshift). In the second case the accretion rate is around 10^2 $M_\odot$/year for all AGN and the mass ranges from $3{\cdot}10^6$ (low redshift) to 10^8 $M_\odot$ (high redshift). Unlike the disks with a low accretion rate, the spectra of the high-accretion-rate disks extend into the soft X-rays. A comparison with observations shows that such disks could produce the soft X-ray excesses claimed in some AGNs. We show also that the sequence of our models with fixed mass and different accretion rates can explain the time evolution of the observed spectra in Fairall 9.

Subject headings: active galactic nuclei - spectra - accretion disks

1 Introduction

The conjecture that Active Galactic Nuclei (AGN) are powered by accreting supermassive black holes (Lynden-Bell 1969) has not yet received a convincing proof. Theoretical arguments based on the efficiency of energy release, rapid variability and superluminal expansion (Blandford 1992) strongly support this hypothesis. However, the mechanism by which the black hole powers the AGN is still unknown. There are at least three classes of models for this mechanism: spherical accretion, disk accretion and dynamo models (Price 1991). In particular physical situations they can be fairly distinct, as for example in disks powered by small scale turbulent viscosity, which may not be driven by a dynamo. In other cases they are closely related.

Although ground- and space-based data have improved considerably, even the most advanced observational techniques still are not able to resolve the innermost parts of AGN. Therefore, accretion flow close to the central engine (within 0.1 pc from the center) can be studied only indirectly. Additional complications are introduced by possible reprocessing of the central radiation out at larger radii.

In this paper we discuss a particular aspect of the accretion paradigm for AGN—namely the predictions of slim accretion disk models for the observational appearance of an accreting nonrotating black hole. We use here non self-gravitating optically thick disk models. In Section 2 properties of optically thick accretion disk models and the results of previous studies of AGN spectra are summarized. In Section 3 the comparison between structure and spectra of thin and slim disk models is presented. General properties of slim disk spectra together with the observed AGN spectra are subject of Section 4. Variability is discussed in Section 5 and we conclude our paper with a summary in Section 6.

2 Spectra of AGN in the framework of accretion disks

One of the most energetically dominant observed features in the continuum spectrum of quasars is the "Big Blue Bump" (hereafter BBB), extending from the optical to the ultraviolet, rising above extrapolations of the infrared continuum. Variability studies suggest that this may be a separate component from the infrared since it varies much more strongly. The beginning of the bump is marked by an inflection around a well-defined wavelength of 1 μm. How far it extends into EUV or soft X-ray is not known yet. This BBB has most often been interpreted as thermal emission from an optically thick geometrically thin accretion disk. Following a promising suggestion by Shields (1978), Malkan & Sargent (1982) and Malkan (1983) showed that the strong BBB of most QSOs and luminous Seyfert 1 galaxies can be well-fitted with simple models of geometrically thin Keplerian disks. Already at that time, two objections to thin disk models were discussed. They seem to predict too high linear polarization of the UV continuum (e.g., Webb & Malkan 1986) or too strong a Lyman limit jump (Sun & Malkan 1987). The geometrically thin accretion disk model for QSO has also been criticized on the ground that it requires luminosities near or in excess of the Eddington luminosity so that it is not self-consistent. Recently, synchronous optical-UV variability has been observed for a few Seyfert galaxies (NGC 5548 is the best example). This may contradict a thin disk prediction that most of the optical thermal continuum is emitted from larger radii (where the temperature is lower) than most of the UV continuum. The observational arguments mentioned above are discussed by e.g. Malkan (1992), Kinney (1994), Collin - Souffrin (1994). Sophisticated accretion disk models have been calculated and alternatives have been proposed, which have major weaknesses of their own. Although the issue is not free from controversy, it is fair to conclude that, after considerable observational and theoretical effort, optically thick accretion models remain a leading possible explanation for the Big Blue Bump.

In many sources, the Einstein IPC and EXOSAT satellites observed ultrasoft (0.3 keV and below) excess flux above extrapolations of the hard X-ray power law (Arnaud et al. 1985, Wilkes & Elvis 1987, Turner & Pounds 1989, Masnou et al. 1992, Comastri et al. 1992). The soft X-ray excess is generally better fitted by the curved, thermal spectra models rather than a second steep power law component (Urry et al. 1989, Weaver 1993). There are suggestions that it is the same physical component as the ultraviolet BBB. Some more recent ROSAT PSPC spectra do not seem to confirm this, as they are mostly well fitted by a single power-law (Laor, Fiore, Elvis, Wilkes & McDowell 1994). A more reliable interpretation of the shape of the soft X-ray continuum requires observations with high signal-to-noise ratios, good energy resolution, and coverage of a broad energy range, which has been possible, for example, in some simultaneous ROSAT/GINGA observations. Unfortunately the connecting extreme-UV wavelengths are blocked from direct observation by the large Galactic opacity. One alternative is to observe the ultraviolet spectra of very high-redshift quasars (Reimers et al. 1992), however this is complicated by the large number of intervening high-z absorption systems with significant optical depth at the Lyman limit. The other alternative is to go the other side of the Galactic opacity barrier and to observe low redshift quasars in very soft X-rays (e.g., Laor et al. 1994). In either case, the detailed shape of EUV/soft X-ray excess—essential for testing the models—is known only roughly.

2.1 Properties of optically thick accretion disks

Theoretically computed spectra of the thermal radiation emitted by accretion disks depend mainly on two physical parameters: accretion rate of mass supplied to the disk from outside, $\dot{M}$, and the mass of the central black hole, M. Observations determine the absolute luminosity and shape of the energy distribution. To compare them with the calculations we introduce a few useful definitions. The total luminosity, L, of the accreting disk, is related to $\dot{M}$ through:

$$L = \eta \dot{M} c^2, \tag{1}$$

where η is the efficiency at which the gravitational energy is converted into radiation. It has been rigorously shown that the efficiency of a stationary disk accreting onto a black hole equals the binding energy of fluid elements at the inner edge of a disk, r_{in}. For the pseudo-Newtonian potential, which mimics the case of Schwarzschild black hole (Paczyński & Wiita 1980), assuming that the matter falls from infinity,

$$\eta = \frac{1}{4}\frac{r-2}{(r-1)^2} \ , \quad r = \frac{r_{in}}{r_G}, \tag{2}$$

where $r_G = 2GM/c^2$ is the Schwarzschild radius, c is the speed of light and G is the gravitational constant.

It is convenient to express L and $\dot{M}$ in critical units. The most common practice is to take for a critical luminosity the Eddington limit, which is defined as the maximal luminosity of a spherical star in hydrostatic equilibrium:

$$L_E = \frac{4\pi c G M}{\kappa} = \frac{2.5 \cdot 10^{38}}{1+X}\frac{M}{M_\odot}\mathrm{erg/s}, \tag{3}$$

where X is the hydrogen content by mass and it is assumed that the opacity κ is due to electron scattering only. For the critical accretion rate, there are two equally often used definitions. The first, which is used in this paper, is called simply the critical accretion rate and has the form:

$$\dot{M}_C = \frac{L_E}{(\eta)_{max} c^2}. \tag{4}$$

The advantage of this formula is that for sub-Eddington accretion rates $\dot{M}/\dot{M}_C = L/L_E$. It is less convenient for super-Eddington accretion rates. For the pseudo-Newtonian potential $(\eta)_{max}$ is equal to 1/16, as the maximum of binding energy is attained at the marginally stable orbit, $r_{ms} = 3r_G$. In this case

$$\dot{M}_C = \frac{64\pi GM}{\kappa c} = \frac{4.45 \cdot 10^{18}}{1+X} \frac{M}{M_\odot} \mathrm{g/s}. \tag{5}$$

Assuming $\eta_{max} = 1$ (100% efficiency), yields the definition of the Eddington accretion rate:

$$\dot{M}_E = \frac{L_E}{c^2} = \frac{2.78 \cdot 10^{17}}{1+X} \frac{M}{M_\odot} \mathrm{g/s}. \tag{6}$$

For the Eddington accretion rate $\dot{M}/\dot{M}_E = \eta^{-1}(L/L_E)$.

The $L - \dot{M}$ relation for slim accretion disks is shown in Figure 1. It was obtained by constructing a sequence of self-consistent models (see Section 3) for a wide range of $\dot{m} = \dot{M}/\dot{M}_C$ and fixed mass $m = M/M_\odot = 10^8$. The disk luminosities were calculated from the local flux F,

$$L = 2\int_{r_{in}}^{r_{out}} F 2\pi r dr. \tag{7}$$

Figure 1 shows that for $\dot{m} \geq 1$ the luminosity rises only logarithmically with accretion rate. This was first found by Jaroszyński, Abramowicz & Paczyński (1980), Paczyński & Wiita (1980) and Paczyński (1980) in the context of thick accretion disks. Abramowicz, Czerny, Lasota & Szuszkiewicz (1988) showed that it is also the property of slim accretion disks around stellar mass black holes. The $L-\dot{M}$ relation depends very weakly on the mass of the central object, so in fact the solid curve in Figure 1 is similar to that in Abramowicz et al. (1988), with the difference that it now extends to higher accretion rates. However, this relation depends significantly on the form and value of the viscosity. The dependence on both mass and viscosity are connected with the finite size of the disk, constrained by the requirement that the self-gravity of the disk is not important. The solid line in Figure 1 was obtained assuming that the viscous stress tensor, $\tau_{r\varphi}$, is proportional to the total pressure and the dotted line is for $\tau_{r\varphi}$ proportional to the effective pressure defined by $\sqrt{PP_g}$ (see equation (8)). In both cases the proportionality coefficient, α, is taken equal to 0.001.

The luminosity—accretion rate relation has important implications for the interpretation of the observed properties of AGN. Depending on their location in the $\dot{M}$,

M plane, accretion disks have quite different physical properties. Recently, Chen, Abramowicz, Lasota, Narayan & Yi (1995) have demonstrated that all possible thermal equilibria of accretion disks with an arbitrary cooling mechanism (including advection) and with an arbitrary optical depth are four physically different classes. The optically thick disks with small viscosity discussed in this paper are Type I of their four classes of models. This class uses the concepts of thin, slim and thick disks:

a) *Thin accretion disks* ($\dot{m} \leq 0.2$). The relative vertical thickness is very small, $H/r \ll 1$, rotation is described by the Kepler law, $\Omega = \Omega_K$. The pressure gradient in the horizontal direction and accretion velocity are dynamically unimportant. There is a local heat balance: heat generated by viscous stress is radiated away at the same radius through the disk surface. These models are described quite accurately by the analytic Shakura-Sunyaev solution. (For references see Frank, King & Raine 1992).

b) *Slim accretion disks (wide range of* $\dot{m}$*)*. The relative thickness $H/r \leq 1$ need not to be small. Rotation differs slightly but importantly from the Keplerian one. The pressure gradient in the horizontal direction is dynamically important. Slim disk models are described by a set of ordinary differential equations and one must explicitly solve the eigenvalue problem connected with the regularity condition at the sonic radius (which does not coincide with the radius of the marginally stable Keplerian orbit). Heat transport in the horizontal direction (by advection) is an important cooling mechanism. Only numerical solutions are known. (For references see Abramowicz, Czerny, Lasota & Szuszkiewicz 1988).

c) *Thick accretion disks* ($\dot{m} \gg 1$) . The relative disk thickness is large, $H/r \sim 1$, and the disk shape is toroidal, with narrow long funnels along the rotation axis. Rotation is highly non-Keplerian. Because of mathematical complications, the internal physics properties are difficult to study and are known only qualitatively. Surface properties, relevant for the continuum spectra, are described by analytic (but phenomenological) formulae. (For references see Abramowicz, Calvani & Madau 1987).

For small accretion rates ($\dot{m}$ not greater than approximately 0.2) the structure of a disk can be described by thin disk model everywhere except in the innermost region (Section 3). For higher accretion rates several assumptions necessary in the construction of the thin disk model are not valid. For $\dot{m}$ exceeding 1, disks become radiation pressure-supported with electron scattering as the dominant source of opacity. They share many characteristics of the geometrically thick accretion disks even if they do not have toroidal structure. The division between slim and thick disks occurs when the approximation of vertical integration breaks down. A detailed comparison between one- and two-dimensional models is needed to derive a proper range for slim disk model applicability (Papaloizou & Szuszkiewicz 1994).

2.2 Fitting observed spectra

Most previous investigations have compared observations of the BBB with simple thin disk models (type a above). However, several problems with that approach, mentioned at the beginning of Section 2, motivated us in this paper to compare the observations with slim disk models (type b).

The first motivation is that the slim disk models cover a wide range of accretion rate regimes which may be more relevant to most quasars. Within this range there is no sub-Eddington limit, as for thin disk models. We illustrate this in Figure 2 which shows a large number of values of $\dot{M}$ and M obtained from previous fitting to AGN spectra. The investigators, who performed these fittings, assumed that the observed BBB is thermal emission from a standard *thin* accretion disk. For those quasar spectra which were fitted by Kerr disk models, we applied the appropriate efficiency and mass corrections so that all the numbers in Figure 2 refer to Schwarzschild black holes, using the transformation relations found by Sun & Malkan (1989). They showed that in going from an extreme Kerr to a Schwarzschild black hole, $\dot{M}$ decreases by 2.5 times, while M increases by 2.5 times. The empty squares illustrate the results obtained by Laor (1990). We have chosen only those objects from his list which were fitted also by Sun & Malkan (1989), to avoid the comparison of two different data samples, although there is no indication that the results would differ significantly for other samples. The filled squares are the Sun & Malkan (1989) results with the inclination angle, i, taken as in Laor (1990). The results of the fitting performed by Malkan (1983), Wandel & Petrosian (1988), Czerny & Elvis (1987), Sun & Malkan (1988), Band & Malkan (1989), Wandel (1991) and Tripp, Bechtold, Green (1994) are also presented. Most of the objects are located in the wide band of accretion rates, between $\dot{M}$ equal to 0.01 $M_\odot$/year and $\dot{M}$ equal to 100 $M_\odot$/year, governed by the slim disk models. This particular sample includes only a few objects with high redshift. Most of them have $z < 2.0$. It is evident from Figure 2 that many of these fits found values of the parameters $\dot{M}$, M which are outside the range of the applicability of the thin disk theory. Note that all (with one exception) Laor's (1990) points lay well within thin disks range. This is because in his calculations the requirement to satisfy the thin disk approximation was built-in. For quasars with higher redshifts (and very high luminosities) Wandel & Petrosian (1988) derived super-Eddington luminosities. The same was found by Tripp et al. (1994) for a substantial portion of their sample. Padovani (1989), using a completely different approach, came to the same conclusion. Adding the high-redshift quasars to the sample makes our argument in favor of the slim disk models even stronger.

A second motivation comes from the observations which suggest that the BBB may be part of a very broad feature that also extends into the soft X-rays (Arnaud et al. 1985; Czerny & Elvis 1987). The dashed arrows in Figure 2 show the changes in the values of $\dot{M}$ and M after including in the fitting procedure the soft X-ray continuum (Laor 1990).

Finally, as discussed in Section 5, the stability and variability properties of thin disks may make them poorer models for most AGN spectra than slim disks. According to the thin disk theory models with $\dot{m} > 0.01$ and the standard α-viscosity are thermally unstable in their innermost parts. Some non-standard viscosity prescriptions are consistent with models which are everywhere stable.

3 The structure and spectra of thin and slim disks

3.1 The structure of disk models

Slim disk models take advantage of the simplification due to vertical integration as in the case of the standard thin disk models, but at the same time they correctly describe important physical effects which dominate the flow for $\dot{m} > 0.2$, but which are omitted in the standard models. The momentum equation for slim disks retains the inertial term, $v_r(dv_r/dr)$, describing the dynamical importance of the accretion velocity, v_r, and the horizontal pressure gradient, $\rho^{-1}(dP/dr)$. The advective, horizontal heat flux, $v_rT(dS/dr)$ is included in the energy equation. The remaining equations are the same as the Shakura-Sunyaev ones. The pseudo-Newtonian potential (Paczyński & Wiita 1980) is used to describe the gravitational field of the central black hole. The inner boundary condition uses the fact that there is no viscous torque across the horizon of the black hole, while the outer boundary condition states that at large radii the model of the flow is similar to that of Shakura-Sunyaev models. We consider disks of Population I composition X=0.7, Y=0.27, Z=0.03. The opacities are taken from the tables of Cox & Stewart (1970). We construct a set of self-consistent models characterized by the mass of the central object $m = M/M_{\odot}$, rate of accretion $\dot{m}$ and viscosity parameter α to compare with observed AGN properties. The models use a family of different viscosity prescriptions in which the relevant viscous stress tensor component is proportional to the following combination of the total, P, and gas, P_g, pressures:

$$\tau_{r\varphi} = -\alpha P^{1-\mu/2} P_g^{\mu/2}, \tag{8}$$

where μ is a measure of the relative importance of P and P_g in the process of viscous energy generation, and it ranges from 0 ($\tau_{r\varphi}$ proportional to the total pressure) to 2 ($\tau_{r\varphi}$ proportional to the gas pressure). We discuss here two interesting cases when $\mu = 0$ and 1.

We require that the mass of the disk is small in comparison with the mass of the central black hole, so the self-gravity is not important. This sets an upper limit on the accretion rate and, because of the accretion rate—luminosity relation, also an upper limit on the luminosity for given values of m and α. The outer radius is determined by the condition that local self-gravitational instabilities are not present. These instabilities may develop when the disk density exceeds M/r^3 where M and r are the mass of the central object and the radius of the disk respectively. The problem of thermal stability is treated separately in the Section 5. We use only those models which, checked a posteriori, are effectively optically thick. This means that the geometric mean of the total, κ, and free-free, κ_{ff}, opacities multiplied by the surface density, Σ, satisfy the condition

$$\tau_{eff} = \frac{1}{2}[\kappa_{ff}\kappa]^{1/2}\Sigma > 1 \tag{9}$$

The slim disk models discussed in this paper are determined by the above assumptions and by differential equations which describe mass, energy and momentum conservation (see Abramowicz et al. 1988). The structure equations for a simple geometrically thin, optically thick accretion disk can be obtained from the slim disk equations by making appropriate approximations (Szuszkiewicz 1990).

Figure 3 shows the radial structure of the sequence of slim models with different luminosities. We have chosen a disk with black hole mass $10^8 M_\odot$, $\alpha = 0.001$ and $\mu = 0$. Two solid lines illustrate the changes in the location of the inner and outer edges of the disks. It can be seen that for $\dot{m} < 1$ the inner edge is very close to $r_{ms} = 3r_G$. At $\dot{m} = 1$ it changes abruptly and then tends to $r_{mb} = 2r_G$. The radial extent of the disk, defined as the radius where its self-gravity is comparable to the gravity from the black hole, reaches a minimum for $\dot{m}$ around 0.1.

A region of radiation-pressure dominance is situated above the dashed line, and the region of electron-scattering dominance is above the dotted line. In the case of $\tau_{r\varphi} \propto P$ ($\mu = 0$) the models become optically thin in the very inner part of the disk for $1 < \dot{m} < 50$ (hatched region). For higher accretion rates the surface density increases and the disk is again optically thick. The model with accretion rate $\dot{m} = 0.001$ is gas-pressure dominated ($P_r \ll P_g$). The main opacity source is free-free absorption. It is a "clean" example of the Shakura & Sunyaev (1973) "outer" region of the disk. Matter under the conditions described above will radiate as a blackbody. In the model with $\dot{m} = 0.01$, there are several different regions: the innermost ($r < 3.3r_G$) where $P_g > P_r$, $\kappa_{ff} > \kappa_{es}$, then the narrow region ($3.3r_G < r < 4r_G$) where $P_g > P_r$, $\kappa_{es} > \kappa_{ff}$, next ($4r_G < r < 43r_G$) where $P_r > P_g$, $\kappa_{es} > \kappa_{ff}$, then ($43r_G < r < 60r_G$) where $P_g > P_r$, $\kappa_{es} > \kappa_{ff}$, and finally the outermost $r > 60r_G$ where $P_g > P_r$ and $\kappa_{ff} > \kappa_{es}$ as in the innermost one. For higher accretion rates the innermost region shrinks towards the central object and the outermost shifts further away. The whole disk becomes radiation-pressure dominated with electron scattering as the principal opacity source. This is the clean "inner" Shakura-Sunyaev region. For bigger black hole masses the disk reaches the sequence of states just described for lower luminosities.

In the case of $\mu = 1$, Figure 3 looks quite similar. The important differences are that the size of the disk of a given luminosity becomes smaller and that the optically thin region of the disk is not present for any value of $\dot{m}$.

The agreement between the structure and radiative flux of the disk calculated by the slim model and the thin one is satisfactory for the range of accretion rates where the thin approximation holds. This fact justifies usage of thin disk approximation for small accretion rates to evaluate the properties of the flow, such as the density, temperature or local flux, apart from their innermost regions. However, thin accretion disks with higher luminosities were used to interpret the AGN observations, and it is interesting to see how they differ from the slim models. We call thin disk models with parameters outside the range of applicability "extrapolated thin disks". In Figure 4 we show the local flux, temperature, and surface density for two models from the sequence just described with $\mu = 0$ and $\dot{m} = 0.5$ and 1. For higher accretion rates up to $\dot{m} = 50$, models have a very small optically thin part. Following our self-consistency argument we will not consider those models further. Instead, in Figure 5 we present the properties of slim and extrapolated thin accretion disk models for $\mu = 1$. Both the structure and local flux show significant differences, especially for super-Eddington luminosities. For the critical accretion rate we calculated the structure and flux for the extrapolated thin disk using both asymptotic expressions for the region characterized by $P_r \gg P_g$ and $\kappa_{es} \gg \kappa_{ff}$ and numerical solutions of the thin disk equations. Taking into account the very narrow gas-pressure dominated region prevents singular behavior of the surface density.

Super-Eddington models are purely radiation-supported structures (for example the model with $\dot{m} = 5$ in Figure 5) where the only opacity source is electron scattering and the flux is determined by the local effective gravity. In this case the heat flux from the surface may be easily estimated, by analogy to supermassive spherical stars, as

$$F = \frac{c}{\kappa} g \tag{10}$$

where g is the effective surface gravity. Our super-Eddington models have their fluxes equal to the critical one. This is the feature they share with the particular type of thick accretion disk model constructed by Paczyński (1980). Because of our self-consistency criteria, our models cannot give arbitrarily large luminosities, and cannot extend arbitrarily far away from the central black hole. In Figures 6 and 7 the maximum luminosity—mass and radius—mass relations for two different definitions of $\tau_{r\varphi}$ are shown respectively. The disks with $\mu = 1$ are smaller in size and less luminous than those with $\mu = 0$. Comparing these results with similar ones obtained for the toroidal shaped thick disk (Abramowicz, Calvani & Nobili 1980) we can conclude that slim disks cannot reach such high luminosities as thick disks (100 L_E) but they can easily produce moderately super-Eddington luminosities (10 L_E). This can be understood in terms of significant differences in the rotation law (angular momentum distribution).

3.2 The radiation spectrum from the accretion disk

Accretion rate and efficiency determine total luminosity. The spectrum of the radiation emitted from the disk surface depends on its structure and surface temperature, T_S. This temperature plays a similar role as effective temperature in stars. To calculate the spectra we need to know how and where the energy is released. The simplest assumption to make about the emergent spectrum is that it is emitted locally at the rate prescribed by viscous energy transport. The local spectrum of the thermal radiation may be one of three typical distributions: a blackbody, a modified blackbody (where the coherent scattering is important) or a Wien spectrum (where inverse Compton may be important). For an effectively optically thick disk, we assume that the local spectrum is a blackbody or modified blackbody (Rybicki & Lightman 1979), given by

$$I_\nu = \frac{2B_\nu(T)}{1 + (1 + \kappa_{es}/\kappa_{ff}(\nu))^{1/2}} \tag{11}$$

where B_ν is the Planck spectrum and

$$\kappa_{es} = 0.20(1 + X)$$

$$\kappa_{ff}(\nu) \simeq 0.75 \cdot 10^{25} \rho T^{-3.5} x^{-3} (1 - e^{-x})(1 + X)(X + Y)$$

where $x = h\nu/kT$ and Gaunt factor is taken equal to 1. For each disk annulus, we calculated the modified blackbody spectrum, which takes into account the dominance of electron scattering over absorption solving equation (11) together with equation for T_S

$$F(r) = \pi \int_0^\infty I_\nu(T_S, \rho) d\nu \tag{12}$$

where spectral intensity I_ν depends on the opacity, the density and the temperature of the disk and $F(r)$ is the local energy release at a particular radius r.

The overall spectrum is computed by integrating the local spectra over the radial extent of the whole disk

$$F_\nu = 2\pi \int_{r_{in}}^{r_{out}} I_\nu r dr$$

Figure 8 shows the spectra radiated from the thin disk with $\dot{m} = 0.1$ and the extrapolated thin disk with $\dot{m} = 1$ for two different forms of viscosity $\mu = 0$ (solid line) and $\mu = 1$ (dotted line). The main difference in the optical is due to the fact that the more dense, $\mu = 1$, model has a smaller size, as it becomes self-gravitating closer to the central object. The Figure shows the classic thin disk result ($\dot{m} = 0.1$) where the middle of the spectrum approximates an $L_\nu \propto \nu^{+1/3}$ power law. At higher frequencies (in the ultraviolet), this power law is steepened to a slope of roughly zero, by electron scattering, which modifies the emitted local blackbody spectrum. The differences between modified blackbody and blackbody spectra are especially significant for high accretion rates, as it is shown in Figure 9. The comparison of the actual slim and extrapolated thin disk spectra is made in Figure 10. Within the valid range of the thin disk approximation, i.e. for $L < 0.2 L_E$, the slim disk gives the same spectrum as the thin one, as expected. Moreover the small differences in local flux seen in Figures 4 and 5 for sub-Eddington models do not appear in their total spectra at all. Only for super-Eddington models is the difference significant (see Figure 10b). It is particularly pronounced in the EUV, so it is very important to be able to observe quasars at these wavelengths. In the optical or UV the difference between the two spectra are so small that it is impossible to determined systematically how the disk parameters m and $\dot{m}$ would change if we applied the slim disk models instead of the thin ones.

4 Spectra of AGN

4.1 Spectra of AGN in three different redshift bands

We wish to compare slim disk models with the broad range of observed energy distributions of Seyfert 1 nuclei and quasars. Our starting point is the large database of optical/ultraviolet spectra for 80 AGNs observed with IUE and ground-based telescopes described by Malkan (1988), and used in Zheng & Malkan (1993). Since we are not attempting to produce optimized fits to each individual spectrum, we have adopted two statistical procedures to isolate the spectrum of the BBB from these energy distributions, by subtracting the continuum component which dominates at infrared wavelengths. In the first alternative, following Sun & Malkan (1989) we suppose that the infrared continuum is described by a power law of slope -1.3 which continues into optical wavelengths. The normalization for all objects was determined by assuming that one quarter of the observed continuum at 5300 Å in every quasar arises from the power law component. This was the average value found in the large quasar sample fitted by Sun and Malkan, which is a subset of the data we show here. Alternately, we suppose that the infrared continuum is thermal emission from dust grains with temperatures ranging up to the sublimation temperature. We describe their combined emission spectrum with the analytic formulation developed by Malkan (1992): $L_\nu \propto \nu^{-0.7} \times \exp(-\nu/\nu_0)$ with $\nu_0 = 10^{14.06}$ Hz. Again we adopted a single normalization of the infrared component for every quasar, assuming it produces 90 percent of the observed flux at ν_0, the characteristic average value in fits presented in those papers. As discussed there, the dust continuum leads to a significantly higher inferred BBB flux in the red, as can be seen in Figures 11, 12 and 13.

In these Figures we show the energy distributions of the AGN in their rest frame divided into three subsets according to redshift: low with $z < 0.15$ (Figure 11), intermediate with $0.15 < z < 0.7$ (Figure 12), and high with $z > 0.7$ (Figure 13). The first panel of each Figure is a collection of the data obtained from the observed spectra by subtracting the power law, the second shows the same data after subtracting thermal dust emission and the third one gives the result of comparison between them. The observational points which belong to the same object are not connected, because we are not concerned at this point with fitting individual spectra. The line drawn through the cloud of points is the average of the AGN luminosities for a given frequency. The substantial contribution of Balmer continuum and blended Fe II lines is present in the spectral region around log ν =14.85-15.1 making the so called "little bump". The difference between BBB shapes that would have been found had we made individual fits to each quasar spectrum is smaller than this systematic difference that depends on our assumed shape of the infrared component.

Next we compare the mean luminosities and the shapes of the BBB described above with the expectations deduced from the slim accretion disk models. We start from models with the parameters suggested by the previous studies where thin disk models were used. That is, we choose black hole masses in the range $10^8 - 10^{10} M_\odot$ and accretion rates below the critical one. For simplicity we will not discuss inclination effects and all spectra presented in this Section were calculated with cos i=0.5. Generally the models cannot account for the extremely flat energy distribution in the case where a thermal dust infrared component was removed, particularly those with $\mu = 1$, as they are steeper in the optical range. For the infrared power-law subtraction, reasonable fits are obtained. The objects with low redshifts have a very flat energy distribution. The model with $\mu = 0$, $m = 8 \cdot 10^8$ and $\dot{m} = 0.01$ gives the right luminosity but has some difficulties reproducing the shape of the spectrum (Figure 14). Similar fits can be obtained by $\mu = 1$, $m = 10^9$ and $\dot{m} = 0.01$. It should be stressed however that in this particular case it is difficult to determine the observed energy distribution due to additional effects like starlight which must be taken into account. The intermediate redshift objects are fitted quite well with the model $\mu = 0$, $m = 8 \cdot 10^8$ and $\dot{m} = 0.08$ (Figure 15) or with $\mu = 1$, $m = 10^9$ and $\dot{m} = 0.07$. Similarly the observations of high z quasars favor the model with

$\mu = 0$, $m = 10^9$ and $\dot{m} = 0.2$ or $\mu = 1$, $m = 2 \cdot 10^9$ and $\dot{m} = 0.15$ for the power law-subtracted spectra. The best fit for $\mu = 0$ together with an attempt to fit dust-corrected spectrum with the model $\mu = 0$, $m = 1.5 \cdot 10^9$ and $\dot{m} = 0.2$ is shown in Figure 16.

Flat energy distributions suggest the possibility that slim disk models with smaller masses and super-Eddington luminosities can provide better fits to the observations. We explore this suggestion and the results are presented in Figures 14, 17 and 18. It is very difficult to find a satisfactory fit for low luminosity objects. Their optical flux appears to come from the outer parts of the disk which are self-gravitating. The very high accretion rates necessary for obtaining such flat spectra could suggest high starburst activity, as there is enough material for stars to be born. Another more likely explanation is that the majority of the optical flux is *reprocessed* EUV radiation intercepted on its way out from the inner disk. For intermediate objects very high accretion rates are also required. The best fit is for high redshift objects. It is interesting to notice that higher redshift (and thus higher luminosities) require smaller dimensionless accretion rates—the opposite of claims from fitting the previous set of thin disk models.

4.2 Soft X-Ray excess

The low mass - high accretion rate models discussed above extend further into the soft X-rays and can produce the observed excess component in this waveband, while the high mass-low accretion rate models can be responsible only for the optical and UV part of the spectrum. Here we examine the hypothesis that the soft X-ray excess observed in an AGN originates in an optically thick accretion disk.

We have selected three particularly well observed bright, low-redshift AGN (Figure 19) with a high soft X-ray flux relative to their optical emission. Other objects have less pronounced soft-X-ray excesses, while still others show no excess at all. However, the strong soft X-ray-excess AGN are exactly the objects which present the greatest challenge to accretion models. Our choice was largely based on EINSTEIN data. The observations of the bright Seyfert 1 nuclei in Markarian 509 and 841, and the extreme soft-X-ray excess quasar PG 1211+14, are taken from Band & Malkan (1989) - crosses - in Figure 19. And we have added the most recent observations by ROSAT - power law with a bowtie - from Walter & Fink (1993) and joint ROSAT/GINGA data - open squares - from Pounds et al (1994). In general these new data, which provide better energy resolution, give a less dramatic soft X-ray excess. The X-ray spectra were not, in general, measured simultaneously with the longer wavelength data. Nonetheless, possible X-ray variability is not so large that it has obscured the evidence that the spectral turnup in the softest X-rays could come from the high-frequency tail of the BBB.

In Figure 19a we show the fit to the spectrum of Markarian 509 with a disk model which extends up to 0.2 keV (solid line). The disk parameters in this case have the following values: $\dot{m} = 0.94$ and $m = 5 \cdot 10^7$. For comparison we also present a fit to the BBB with $\dot{m} = 50$ and $m = 8 \cdot 10^6$ which extends up to 1 keV (dotted line). In the case of the Markarian 841, the least luminous of the three AGN considered here

(Figure 19b), the corresponding values are $\dot{m} = 0.5$, $m = 2.5 \cdot 10^7$ (solid line) and $\dot{m} = 10^3$, $m = 10^6$ (dotted line). For PG 1211+143 the masses and the accretion rates derived from the fitted models are $\dot{m} = 1.5$, $m = 5 \cdot 10^7$ (solid line) and $\dot{m} = 100$, $m = 10^7$ (dotted line). Extreme soft X-ray fluxes require according to our models very high accretion rates, in absolute units, particularly in the case of the broad disk component in Mkn 841, which may be unlikely. Relativistic correction and rotation of the black hole, which we plan to implement in future studies may give harder spectra at lower accretion rates.

The model spectra fall steeply (exponentially) in the soft X-ray regime, while the majority of observed spectra are less steep (see e.g. Laor et al. 1994). This may indicate that the flux from the optically thick accretion disk extends no further than 0.5 keV. A new generation of accretion disk models with the appropriate treatment of the optically thin part of the flow will provide a more definitive conclusion.

5 Variability

As was shown in Section 3, the thin disk model, within the limits of its validity, gives a reasonable approximation to the observed properties of accretion onto a compact object. The stability problem requires taking into account all details of the accretion process which in the case of the black hole differ significantly from those of accretion onto other compact objects. This can be considered only in the slim approximation since the thin disk assumption discards information about the inner part of the flow which is most relevant for stability. Stability depends very strongly on the viscosity assumption. One way of extracting information about both properties of AGN and the viscosity mechanism itself is to compare predictions from the models with different forms of viscosity with the observed properties of AGN. Here we apply the family of viscosity prescriptions given in Equation (8).

Abramowicz, Czerny, Lasota & Szuszkiewicz (1988) suggested a limit cycle instability can explain the variability of X-ray sources. If this mechanism is present in AGN, one can expect to see not only intensity variations, but also spectral variability, i.e., a varying BBB. A plausible upper limit to the amplitude of variability comes from comparing the flux from the lower stable state of the disk with the flux from the upper stable state. The standard viscosity prescription gives disks with such wide-ranging instability that extremely large flux variations (around three orders of magnitude) would appear to be allowed. With the modified viscosity law, the amplitudes are reduced to one or one and a half orders of magnitude, more consistent with the largest variations seen in normal AGN. This is shown in Figure 20 where the stability regions (from a simple local analysis) of the thin and slim disks in the $\dot{m} - r$ plane are drawn. Similar studies were performed for slim disks around stellar black holes (Honma, Matsumoto & Kato 1991; Szuszkiewicz 1990). The global analysis by Honma et al. (1991) and local analysis by Wallinder (1991) suggests that the disk is stabilized before reaching the upper stable branch of the slim disk solution so that the unstable inner part is smaller in the $\dot{m}$ direction. These results still await confirmation.

We illustrate how this mechanism could work in Figure 21. The difference in the UV flux (for example at 1544 Å) between low and high states is about a factor 20, as was observed in Fairall 9 (Clavel, Wamsteker, & Glass 1989). We have plotted the three characteristic energy distributions for this high-luminosity Seyfert 1 nucleus, corresponding to maximum, minimum and average brightness levels. The IUE data are from Clavel et al. (1989) with simultaneous optical photometry from Glass (1986). As with the quasars, we have corrected the optical fluxes by subtracting an infrared component attributed to either a power law, or thermal dust emission. Even after this correction, it is apparent that the range of variation in the UV (a factor of 10) is greater than the range in the red (a factor of 3.5). This illustrates the typical trend for AGN spectra to become harder when brighter.

Let us first discuss the spectrum corrected for thermal dust emission. We will use here models with $\mu = 1$, as they fit data better. The smaller BBB at the luminosity minimum is taken as the energy distribution arising from the disk with $m = 2 \cdot 10^8$ and $\dot{m} = 3.8 \cdot 10^{-2}$. At maximum light, the spectrum is represented by the model with the same mass and the $\dot{m} = 0.65$. The intermediate state is fitted by the model with $\dot{m} = 0.09$. In the case of the spectrum corrected for the power law the best fits are obtained using spectra calculated in the simple sum-of-blackbodies approximation. The sequence of models fitting the observations has mass $m = 2 \cdot 10^8$ and $\dot{m} = 0.03$, 0.08, and 0.6 for minimum, intermediate and high states. The instability operates in the inner part of the disk (see Figure 20). Predicted thermal instability timescales for the variability is of the order of 1000^d, depending on α. This picture is in rough agreement with the proposed mechanism for variability.

It is intriguing that slim disks tend to stabilize at the highest accretion rates. This might suggest that the most luminous AGN should show little UV variability. At intermediate accretion rates, for sub-Eddington disks, we might expect the BBB and the soft-X-ray excess to vary more or less directly together. In highly super-Eddington disks, the UV spectrum could remain steady while the X-ray spectrum brightened and hardened. (Note that in these optically thick models, no Comptonization takes place). However, our investigations presented here are too approximate to make strong conclusions about detailed spectral variability properties. This will require calculation of the full time evolution for such models (Miller & Szuszkiewicz 1995).

Another interesting feature of supercritical models is that they give similar radiated energy distributions from disks with different accretion rates. The reason is that for higher accretion rates the heat trapped in matter becomes important, and the flow of matter induces non-negligible advective horizontal heat flux. Thus, for higher accretion rates, efficiency decreases and luminosity increases not in proportion to the accretion rate but more slowly (Figure 1).

6 Conclusions and discussion

Within the range of the validity of the thin disk approximation, i.e. for $L < 0.2 L_E$, the slim disk reproduces all characteristics of the thin disk, as we expected. Moreover the slim disk extends the standard model to higher luminosities, which might be necessary to explain the luminous quasars. The slim disk models provide the stabilizing mechanism over a range of accretion rates. The super-Eddington models offer the same quality of fits to the observations as the sub-Eddington ones and have the advantage of also being able to explain the soft X-rays spectra.

It is difficult to compare our results with previous studies, mostly because they differ in essential points. We start from the self-consistent slim disk models and treat the spectra in a very simplified way. The others start from very simplified disk model and include important physical effects in the calculations of the spectra. Moreover they used a much bigger viscosity parameter, which at higher accretion rates requires proper treatment of the optically thin part of the disk.

In the case of a geometrically thin accretion disk it is possible to consider the vertical and radial disk structures separately. It is also reasonable to assume local heat balance. In order to calculate a spectrum it is sufficient to divide the disk into a number of one-dimensional layers and to solve the radiative transfer there. Many sophisticated accretion disk models have been calculated since the first simplest local sum-of-blackbodies approximation. The slim accretion disk model takes into account non local flux generation, but still radiative transfer is considered only in the vertical direction. Solving radiative transfer only in the vertical direction, justified when the disk is very thin, leads to the so called "lags" of the optical continuum behind (or ahead of) the UV continuum (depending on the propagation direction of the perturbation). Such models predicts long lags as the optical radiation is generated far away from the place where the UV is radiated, and the wavelike disturbances travel more slowly than light. Quasi-simultaneous optical and UV spectra of NGC 5548 obtained by a combined IUE and ground-based monitoring campaign (Clavel et al. 1991 and Peterson et al. 1991) show that the average lag of the optical continuum behind the UV continuum is no larger than 4 days. In NGC 4151 a similar limit is no larger than 3 days. In Fairall 9, there are indications that an optical-UV lag has been detected and it is 140 days. A similar detection was found for 3C 273 and the estimated lag is no larger than 40 days.

When the disk is geometrically and optically thick local energy balance cannot be assumed, since the heat generated by dissipation can travel in any direction before reaching the surface. The energy produced at some point inside the disk will not just diffuse vertically but may emerge from any part of the surface. In such disk we do not expect to observe long lags.

Two very important improvements remain to be made. One is to include self-consistently optically thin part of the disk. We would like to mention here that there are many new developments in the area of optically thin advection-dominated accretion flows (e.g., Abramowicz, Chen, Kato, Lasota, Regev 1995; Narayan & Yi 1995; Chen et al. 1995; Björnsson, Abramowicz, Chen, Lasota 1995). Second, is to solve the radiative transfer equation in geometrically and optically thick accretion disks.

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Figure Captions

Figure 1: The total luminosity - accretion rate relation for slim disk models with the two different forms of viscosity: $\tau_{r\varphi} = -\alpha P$ (solid line), $\tau_{r\varphi} = -\alpha\sqrt{PP_g}$ (dotted line). In both cases α =0.001.

Figure 2: The values of $\dot{M}$ and M obtained by fitting the observed spectra to those predicted by theory:

□ Laor (1990)
□ Sun & Malkan (1989)
× Sun & Malkan (1988), Band & Malkan (1989), Wandel (1991), Czerny & Elvis (1987)
◇ Padovani (1989)
∗ Tripp et al. (1994)
solid line rectangular - quasars - Wandel & Petrosian (1988)
dotted line rectangular - Seyferts - Wandel & Petrosian (1988)

Figure 3: The radial structure of the sequence of models with different luminosities. The mass of the central black hole is $10^8 M_\odot$, $\alpha = 0.001$, and $\mu = 0$. The size of the disk is the distance between two solid lines. The dotted line marks the place where $\kappa_{es} = \kappa_{ff}$ and the dashed one where $P_g = P_r$. In the small hatched region in the left corner the models become effectively optically thin.

Figure 4: Local flux (a), temperature (b), surface density (c) for the thin (dotted lines) and slim disk models (solid lines) with $m = 10^8$, $\alpha = 10^{-3}$, $\mu = 0$ and $\dot{m} = 0.5$. Similarly (d), (e) and (f) for the $\dot{m} = 1$.

Figure 5: Local flux (a), temperature (b), surface density (c) for the thin (dotted lines) and slim disk models (solid lines) with $m = 10^8$, $\alpha = 10^{-3}$, $\mu = 1$ and $\dot{m} = 0.5$. Similarly (d), (e) and (f) for the $\dot{m} = 1$. Figures (g), (h) and (i) are also for $\dot{m} = 1$ but instead of using the numerical solution for standard thin disk model we used the asymptotic Shakura-Sunyaev formula. Figures (j), (k) and (l) show the properties of the models with $\dot{m} = 5$.

Figure 6: The maximum possible luminosity of non-self-gravitating slim accretion disk orbiting a central black hole as a function of its mass for two different viscosity prescriptions: $\mu = 0$ (solid line), $\mu = 1$ (dotted line).

Figure 7: The outer radius for the slim disks with maximal luminosity for two different viscosity prescriptions: $\mu = 0$ (solid line), $\mu = 1$ (dotted line).

Figure 8: The spectral distributions for the models with $\dot{m} = 0.1$ and $\dot{m} = 1$ for different viscosity prescriptions: $\mu = 0$ (solid lines), $\mu = 1$ (dotted lines).

Figure 9: The comparison between the spectra of the $\mu = 1$ disks with $\dot{m} = 0.1$ and 1 calculated as the superposition of modified blackbodies (dotted lines) and simple black bodies (solid lines).

Figure 10: The slim disk spectra (solid lines) versus the extrapolated thin one

(dotted lines) a) for $\dot{m}$= 0.5, 1 b) for $\dot{m} = 5$.

Figure 11: Energy distributions for 23 quasars with $z < 0.15$. a) after correction for an infrared power law, b) after correction for thermal infrared emission from hot dust, c) the difference between the average distributions in the case a) and b).

Figure 12: Similarly as in Figure 11 but for 45 quasars with $0.15 < z < 0.7$.

Figure 13: Similarly as in Figure 11 but for 37 quasars with $z > 0.7$.

Figure 14: The attempt to fit the low-redshift objects with two models: first with $m = 8 \cdot 10^8$, $\dot{m} = 0.012$ and second with $m = 3 \cdot 10^6$, $\dot{m} = 10^3$

Figure 15: The best fit to the intermediate-redshift objects: $m = 8 \cdot 10^8$, $\dot{m} = 0.08$

Figure 16: The best fits to the high-redshift objects: for the power law-corrected spectra: $m = 1.5 \cdot 10^9$, $\dot{m} = 0.2$, and for the dust-corrected spectra: $m = 2 \cdot 10^9$, $\dot{m} = 0.2$

Figure 17: The best fit to the intermediate-redshift objects: for the power law-corrected spectra: $m = 2 \cdot 10^7$, $\dot{m} = 250$, and for the dust-corrected spectra: $m = 2 \cdot 10^7$, $\dot{m} = 500$

Figure 18: The best fits to the high-redshift objects: for the power law-corrected spectra: $m = 8 \cdot 10^7$, $\dot{m} = 70$, and for the dust-corrected spectra: $m = 8 \cdot 10^7$, $\dot{m} = 130$

Figure 19: The best fits to the three low-luminosity AGN with spectra observed into the soft X-rays a) MKN 509 - $m = 5 \cdot 10^7$, $\dot{m} = 0.94$ (solid line), $m = 8 \cdot 10^6$, $\dot{m} = 50$ (dotted line), b) MKN 841 - $m = 2.5 \cdot 10^7$, $\dot{m} = 0.5$ (solid line), $m = 10^6$, $\dot{m} = 10^3$ (dotted line), the dashed line shows the spectrum for $m = 10^6$, $\dot{m} = 10^3$ if the disk structure is extrapolated beyond the self-gravity point, c) PG 1211+143 - $m = 5 \cdot 10^7$, $\dot{m} = 1.5$ (solid line), $m = 10^7$, $\dot{m} = 100$ (dotted line). See text for more details.

Figure 20: The stability regions in $\dot{m} - r$ space for thin (a) and slim (b) accretion disks with $m = 10^8$, $\alpha = 0.001$ and different values of μ.

Figure 21: The spectral evolution in the source Fairall 9 and the best fits for a) spectrum corrected for an infrared power law b) spectrum corrected for thermal dust emission.