VARIABILITY AND SLIM ACCRETION DISKS

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Abstract. Many compact galactic and extra-galactic sources have a luminosity in the slim accretion disk regime, i.e. $L/L_{\rm E} \sim 1$, where $L_{\rm E}$ is the Eddington luminosity. The correspondingly large accretion rates diminish the relevance of variability interpretations based on the thin disk model. This paper explores the possible connection between variability in AGN and local instabilities in slim disks, and points out some relevant areas of future research.

Key words: Black holes, accretion disks, variability

1. Introduction

Accretion disks surrounding massive central objects are probably the main power source in compact sources, such as AGN. Models of such objects often employ the standard thin disk model (Shakura & Sunyaev, 1973, 1976), in spite of the well-known fact that luminosities comparable to the Eddington one imply a break-down of the thin disk approximation. Thin disks have also unphysical singularities at the inner edge, due to an oversimplified treatment of the inner region. In contrast, slim accretion disk models have an accretion rate $\dot{m} = L/L_{\rm E} \sim 1$, where $L_{\rm E} = 10^{46}\, M_8$ erg s^{-1} is the Eddington luminosity and M_8 the central mass in units of $10^8\, M_\odot$. The treatment of the inner region take into account transonic radial motion, non-Keplerian rotation, advection of heat into the presumed black hole as well as radial pressure and velocity gradients, none of which are included in the standard model (e.g., Abramowicz et al. 1989; Wallinder 1991a,b; Chen & Taam 1993). Another advantage is the limited number of input parameters, comprising $(\alpha, \dot{m}, m)$, where α is the standard viscosity parameter and m the central mass in solar units. If AGN variability is due to instabilities in slim disks, information about these parameters may be deduced. Combining for instance the inferred central mass with a size estimate would provide additional evidence of black holes in galactic nuclei.

The main aim of this paper is to study the local stability of slim disks as a function of radius. This will provide information about where the various instabilities operate and what time scales they have.

2. The radial profile of the luminosity

The issue of where most of the luminosity is generated is essential, since the most noticeable variability should come from the most luminous region of the disk. If one plots radial profiles of flux against radius, one usually finds that the flux has a maximum at $x = r/r_{\rm g} \sim 5$, where $r_{\rm g} = 10^{-5}\, M_8$ pc is the Schwarzschild radius. Many authors therefore assume that most of the variability arises close to $x \sim 5$.

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However, the emitting *area* around this radius is rather small compared to the one for the whole disk. What seems more relevant is the radial dependence of the integrated flux. Fig. 1a shows the obtained luminosity profile for the emission from both sides of the disk. The examples shown are for two accretion rates, $\dot{m} = 0.01$ and 6.3. Here and henceforth, the parameters $(\alpha, m) = (10^{-3}, 10^{7})$ were adopted. As can be seen, the luminosity rises quickly but approaches a constant value only when $x \gtrsim 10^3$.

In Fig. 1b it has been assumed that all the luminosity is produced within $x \lesssim 10^3$, so that the scaled luminosity $L/L_{\mathrm{max}} = 1$ at $x = 10^3$. Apparently ~ 80 % of the radiation comes from the region $x \lesssim 10^2$, whereas only about 30 % arises within $x \lesssim 10$. This argues against the notion of a "preferred" radius around $x \sim 5$ where most of the variability is generated. The combined effect from many radii may be a better interpretation.

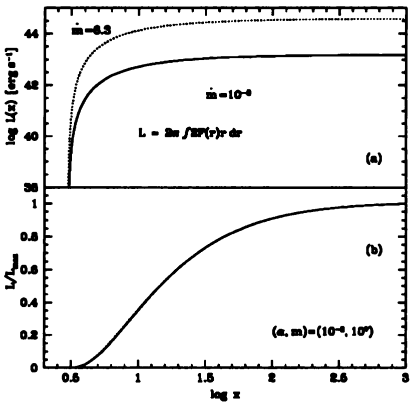

Fig. 1. **(a):** Integrated flux profiles from slim disks, i.e. the luminosity emitted within the radius $x = r/r_g$, where r_g is the Schwarzschild radius. The luminosity approaches a constant value only when $x \gtrsim 10^3$. **(b):** The same luminosity profiles, but scaled in terms of $L_{\mathrm{max}} \equiv L(10^3)$. Due to the almost parallel curves in (a), values virtually coincide. The fraction of the total luminosity which arises within $x \lesssim 10$ and $\lesssim 10^2$ is ~ 30 and ~ 80 %, respectively.

3. Method of stability analysis

The radial structure of the disk is governed by the conservation laws of mass, momenta and energy. Together with e.g. an equation of state they form of complete set of equations. The time-independent equations are solved numerically, in order to obtain the slim disk equilibria. The resulting solutions are fed into the coefficients of a fourth-order dispersion relation, which is obtained from the linearly perturbed time-dependent equations. The analysis is local, so that boundary conditions are avoided. The dispersion relation is solved numerically, yielding growth rates for the

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thermal/viscous and the two acoustic modes in various parts of parameter space.

4. Results

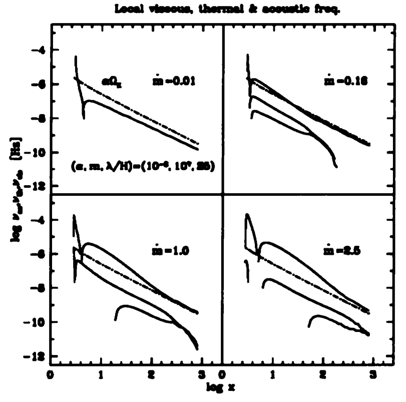

Fig. 2. Local instability frequencies against radius. The dash-dot curve corresponds to the frequency $\alpha\Omega_K$. The modes (solid curves) can be distinguished through their different growth rates, which increase in the order viscous-thermal-acoustic. However, in the top/left fig. the accretion rate is so low that no thermal/viscous instabilities are present. The only unstable mode is the outward propagating acoustic one, and the inward propagating one in the innermost region. In the top/right fig. the thermal/viscous instabilities turn on at about $x \sim 10^2$. Advection cooling results in a stable inner region, whose extent increases with $\dot{m}$. The time scales vary from $\sim 10^2$ yrs in the outer disk to fractions of days in the inner.

Fig. 2 shows thermal, viscous and acoustic instability frequencies as function of radius. For $\dot{m} = 10^{-2}$, only the outward propagating acoustic mode is unstable over a large fraction of the disk, whereas the inward propagating acoustic mode becomes highly unstable in the innermost region. When $\dot{m} \sim 0.1$, the viscous and thermal instabilities turn on at around $x \sim 10^2$, but in general they have much lower growth rates than the acoustic modes. This implies that the advection cooling in the inner region stabilizes the viscous mode first, then the thermal and lastly the acoustic modes. It can also be noted that the time scales adhere to the standard $(\alpha\Omega_K)^{-1}$ one only at specific combinations of the input parameters, i.e. approximating instability time scales with the latter value may be inappropriate in general. Another thing to note is the huge span of time scales across the disk, from hundreds of years in the outer part to fractions of days in the inner one.

5. Conclusions

Despite the rapid increase of the luminosity profile, observed variability should come from an extended region (say $x \lesssim 10^2$) instead of a narrow annulus around

$x \sim 5$. The selection of a few radii due to wave trapping inside the epicyclic barrier at $x \sim 4$ (Okazaki et al. 1987; Nowak & Wagoner 1991) may be irrelevant, since only a minor fraction of the total luminosity arises within $x \lesssim 10$. Evaluation of variability time scales may be hazardous without knowledge of detailed stability properties. As the examples above show, the whole range from totally stable to partially unstable or fully unstable disks is possible. The result depends partly on which type of instability is considered, partly on the position in parameter space. The range of time scales is rather large, so it should come as no surprise that variability power spectra often show no significant peaks.

6. Future work

A growing number of researchers have realized that slim accretion disks constitute a good framework in which additional physics may be included. Thus, a number of projects are under development at present. One will attempt to include an optically thin plasma near the inner region, in order to produce the observed hard X-rays. Another will attempt to solve the time-dependent slim disk equations. The combination of these will allow computation of theoretical power spectra, which convolved with the detector response of whatever X-ray satellite will produce results which can be compared with observations in detail.

As pointed out by Lin et al. (1990), a realistic accretion disk has probably a sound speed which decreases in the z-direction. It follows that a wave front which starts out perpendicular to the disk plane will be refracted into the corona. If a sufficient amount of energy can be transferred to the modes, the result may be acoustic coronal heating. Thus, information about the acoustic instability frequencies may be propagated into the X-ray producing region.

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