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INVITED REPORT

Microquasar: Disk Models

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Abstract Basic disk models are reviewed with special attention on the dynamics of near- or super-critical accretion regimes. High accretion-rate flows are observed in many different systems and interaction between radiation and gas is key physics in this regime. GRS 1915+105 seems to probe the presence of transitions between the standard-disk and slim-disk branches. At even higher accretion rates ($> L_{\rm E}/c^2$), significant photon trapping effects appear, leading to spectral softening, because hard photons are more effectively trapped by the flow.

Key words: accretion physics — black holes — radiation processes — photon trapping

1 INTRODUCTION

The discovery of microquasars has opened a new era of the research of accretion flow and jets. The emergence of superluminal jets from stellar-mass compact objects promotes theoretical study regarding the jet collimation/acceleration mechanisms and disk-jet connection. Because of their intrinsically shorter time variations, important constraints have been imposed on the conditions of the accretion flow producing jets. Equally important are peculiar behaviors of a microquasar, GRS 1915+105 (Belloni et al. 2000), since its diversity of time-dependent properties requires re-considerations of our fundamental understanding of accretion flow. In particular, its repetitive outbursts may be understood in terms of a disk instability associated with a disk shining around the Eddington luminosity ($L_{\rm E}$).

This paper consists of three parts. First, we briefly explain the slim disk model proposed by Abramowicz et al. (1988). This is a representative disk model at high accretion regimes (Kato et al. 1988) with $\dot{M} > L_{\rm E}/c^2$ (where c is the speed of light). Second, we discuss the relaxation oscillation type behavior of high $\dot{M}$ disks in the context of bursting behavior of GRS 1915+105. Finally, we elucidate the theory beyond the slim disk model.

2 SLIM DISK MODEL

When we discuss properties of the disk which can produce energetic jets as are observed in microquasars, we need to extend the standard disk model towards the high-luminosity regimes. Here, we explain the basic properties of the slim disk model, representative disk model near the Eddington luminosity.

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2.1 What is a slim disk?

As is widely recognized, the standard disk model is very successful in explaining various properties of accretion systems, however, it cannot directly apply to high accretion-rate system, because basic assumptions and simplifications made in the standard-disk model break down at high accretion rates. For example, the radial pressure gradients and (inertial) terms are no longer negligible, compared with gravity and centrifugal forces. Therefore, the momentum conservation becomes,

$$v_r \frac{dv_r}{dr} = -\frac{1}{\Sigma}\frac{d\Pi}{dr} + r\left(\Omega^2 - \frac{GM}{r^3}\right), \tag{1}$$

where $\Sigma(\equiv \int \rho dz)$ is surface density, $\Pi(\equiv \int pdz)$ is height integrated (total) pressure, Ω is angular frequency, and we used the cylindrical coordinates, (r, φ, z).

More importantly, advection of photon entropy can never be omitted in the energy equation; that is,

$$\frac{1}{2} v_r \Sigma T \frac{ds_{\rm rad}}{dr} = \frac{9}{8}\nu\Sigma\Omega^2 - \frac{4acT^4}{3\tau}, \tag{2}$$

where $s_{\rm rad}$ denotes the radiation entropy, a is radiation constant, τ is optical depth of the disk, and ν is kinematic viscosity, which is in the α prescription,

$$\nu = \frac{2}{3}\alpha c_{\rm s} H, \tag{3}$$

with $c_{\rm s}$ being sound velocity and H being the scale height of the disk, respectively. In Eq. (2), the term on the L.H.S. represents the advection term (of radiation entropy), while the two terms on the R.H.S. represent viscous heating and radiative cooling, respectively. Since these equations are differential equations, we need to solve the flow structure numerically, adopting the transonic boundary condition; that is, we require that flow should pass the transonic point, outside which the flow is subsonic ($v_r < c_{\rm s}$), and inside which it is supersonic (Muchotrzeb & Paczyńsky 1982; Matsumoto et al. 1984).

2.2 Temperature profiles

Figure 1 depicts the calculated temperature distribution. Solid, dotted, dashed, and small dotted curves are the effective temperature profiles of the optically thick disk as functions of accretion rates. Here, we take a mass of black hole to be $10M_{\rm sun}$. There are two effects appearing when the accretion rate exceeds the critical value of about $10L_{\rm E}/c^2$. The first one is the changes of the temperature slopes; The effective temperature profiles become flatter, from $r^{-3/4}$ to $r^{-1/2}$. The second effect is the shift of the apparent innermost radius. It is 3 $r_{\rm S}$ in the standard-disk regimes (for the case of a disk around a non-rotating black hole), whereas about 1 $r_{\rm S}$ in the slim-disk regimes. Therefore, we expect the innermost radius of the disk to shift from $3r_{\rm S}$ to 1 $r_{\rm S}$ as luminosity increases. This may solve the "too high hot disk problem" in ULXs (Makishima et al. 2000). Let us check, next, if this trend can actually be observed in real data.

To compare with the observations, we fit the theoretical spectra by the Multi-color disk (MDC) model proposed by Mitsuda et al. (1984). This model has two fitting parameters: $T_{\rm in}$, temperature of the innermost region having the maximum temperature, and $r_{\rm in}$, size of the region emitting with blackbody radiation of temperature, $T_{\rm in}$. It is known that this model fitting can give a good black-hole mass estimations. Further, the observations show that $r_{\rm in}$ stays constant regardless of luminosities, even when luminosity changes substantially (see Ebisawa 1999).

Figure 2 represents the fitting results plotted against $T_{\rm in}$ and bolometric luminosity. This plane is sometimes called the X-ray H-R diagram. The standard disk predictions are drawn as straight lines. As long as the innermost radius stays constant, every object should evolve

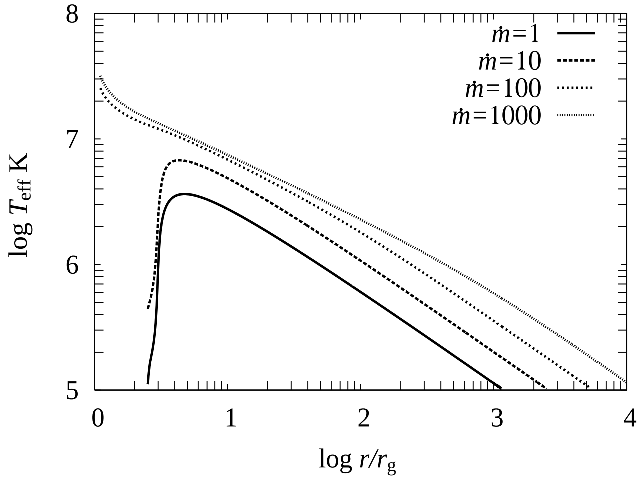

Fig. 1 Temperature profile of the disk as a function of mass accretion rate. (After Watarai et al. 2000)

parallel to the constant-mass lines on this plane. However, some sources, like IC342 S1 and M81 X-6, show clear deviations from those trends in such a way that $r_{\rm in}$ decreases as L increases (see Kubota et al. 2001, also Kubota 2004 in these proceedings). Furthermore, Ebisawa et al. (2003) performed a direct model spectrum fitting of IC342 including the response of ASCA instrument. They revealed that the black hole mass which is derived from the standard disk model fitting varied with different observation epoch. This result is unphysical, because the black hole mass does not change such a short observational time-scales. On the other hand, the slim-disk model also gives acceptable fits and predicts a constant black hole mass even if the observation epoch changes. These could be a manifestation of the photon trapping effects, thus supporting the slim-disk picture of these sources.

3 CASE OF GRS 1915+105

The slim-disk state seems to appear also in a microquasar, GRS 1915+105. In this section, we discuss how to constrain theoretical disk models of GRS 1915+105.

3.1 Modeling GRS 1915+105

In order to understand the physics of accretion flow in GRS 1915+105, Yamaoka et al. (2002) made spectral fitting to the peak and the valley state of GRS 1915+105 during its bursting phase separately with the multi-color disk model. The typical burst rise time is a few seconds, and the duration time is about a few $\times$ 10 seconds. These timescales are roughly consistent with the thermal-viscous time scales of accretion disk. The results are informative: the peak and valley states, respectively, are consistent with the standard and slim-disk model. This strongly supports the idea that the bursting behavior of this system could be due to thermal relaxation oscillations between the standard- and slim-disk branches, as was originally pointed out by Honma et al. (1991), and was later confirmed by Chen & Taam (1993) and Szuszkiewicz & Miller (1998).

When we solve the structure of high luminosity disks shining around the Eddington luminosity, we notice that the thermal equilibrium curves is S-shaped (see figure 3). The middle and

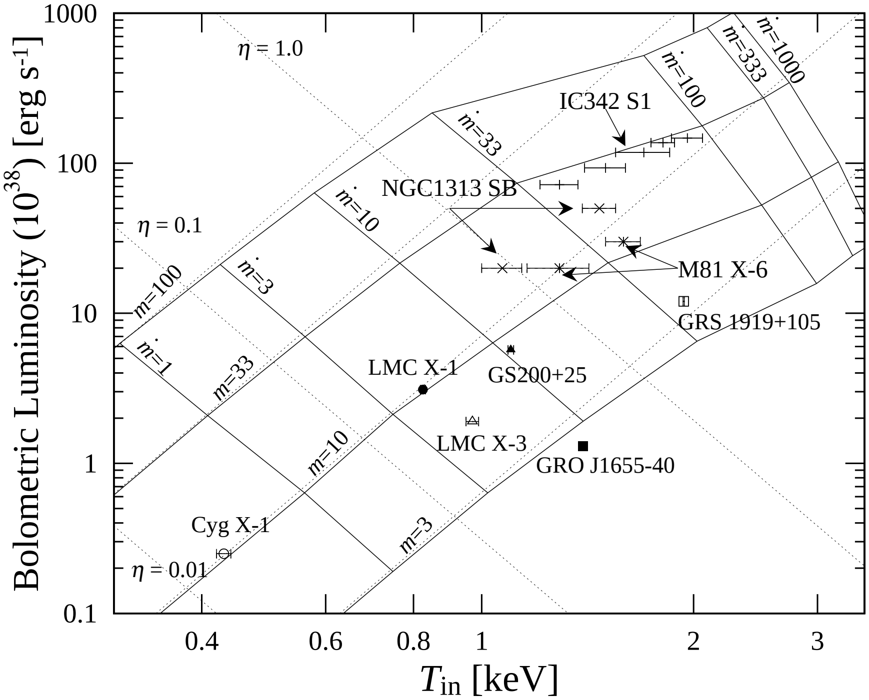

Fig. 2 Theoretical X-ray H-R diagram superposed with observational points. The calculations clearly show a tendency that $r_{\rm in}$ decreases with increase of L when L approaches the Eddington luminosity, $L_{\rm E}$. Note that general relativistic corrections are not included, so this figure only presents rough tendency. (After Watarai et al. 2001)

lower branches, respectively, correspond to radiation and gas pressure-dominated part of the standard disk, while the upper branch corresponds to the slim-disk state. The middle branch, i.e., the radiation pressure-dominated part of the standard-type disk, was shown to be thermally unstable (Shibazaki & Hoshi 1975; Shakura & Sunyaev 1976).

Namely, the middle branch of the S-shaped thermal equilibrium curve is unstable, whereas the other high and low branches are stable. Therefore, a disk cannot stay in the middle branch but alternates between the high and low branches. This is a basic idea of the disk-instability model for GRS 1915+105.

The most intriguing fact is that such transitions are propagated radially, transforming one state to another. Such nonlinear evolutions can be simulated numerically. We performed calculations, paying special attention to the innermost part of the flow (Watarai & Mineshige 2003). The results are displayed in figure 4. We could reproduce theoretically substantial reduction in $r_{\rm in}$ during the burst phase, in good agreement with the observations by Yamaoka et al. (2002).

3.2 Is the inner-edge of the disk at $3r_{\rm S}$?

Here, we need to make an important remark on the innermost radius. Maybe it is widely believed that the inner edge of the disk is always at $3r_{\rm S}$ for a non-rotating black hole. We wish to stress, however, that this is not always the case.

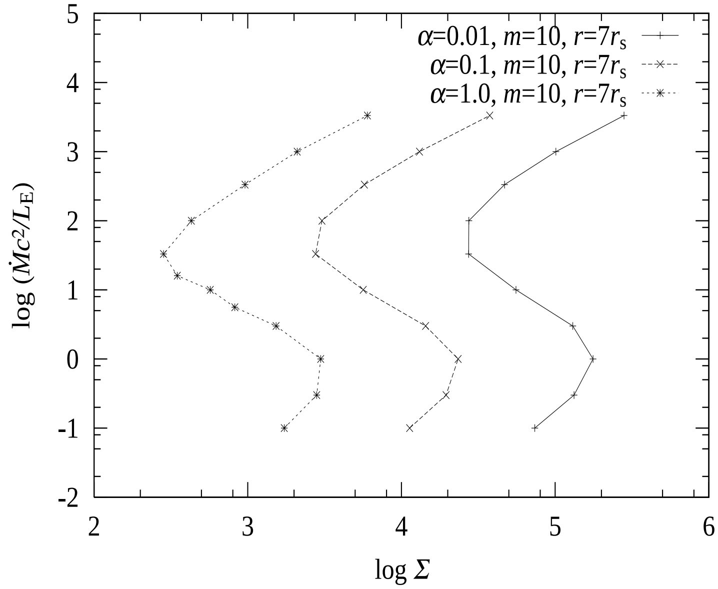

Fig. 3 S-shaped thermal equilibrium curve of a high-luminosity disk. Solid, dashed, and dotted lines represent different viscosity parameters, α=0.01, 0.1, and 1.0, respectively. The middle branch is thermally unstable so that relaxation oscillations between the upper and lower branches are inevitable consequence. Data points are from figure 5 of Watarai & Mineshige (2001).

The widely prevailed belief is based on the classical argument on the stability of circular orbits. Let us consider a test particle, which is in force balance between the centrifugal force and the gravity force due to the central object. We perturb a location of the test particle to see if the particle return to the original position or not. If yes, the orbit is stable, and otherwise it is unstable. Then, we find for a non-rotating black hole that the circular orbit is unstable at $r < 3r_S$, when general relativistic effects are considered.

This analysis can no longer apply to the slim disk case, because inertial and pressure gradient terms are not negligible in the slim-disk regimes (see equation 1). In other words, there are no force balance. Therefore, *the usual stability analysis (which is based on the assumption that an unperturbed state is in equilibrium) cannot apply here.* There is no solid ground to believe that the innermost radius is 3 r_S!! Nevertheless, people simply believe that the disk inner edge is always at 3 r_S for a non-rotating black hole, which is a wrong assumption. Then, how large is the observed edge of the disk? We need to calculate radiation efficiency at each radius and sum up all the contributions to specify the radius inside which practically no radiation can reach observers. We have found that it is significantly below 3 r_S.

4 BEYOND THE SLIM DISK MODEL

Finally, we discuss a disk model beyond the slim disk model. We will argue that the slim disk model does not fully take photon-trapping effects into account.

4.1 What is missing in the slim-disk model?

Let us recall what photon trapping is (Begelman 1978). As accretion rates increase, surface density (or Thomson optical depth) of the flow also increases, and, therefore, it takes a longer

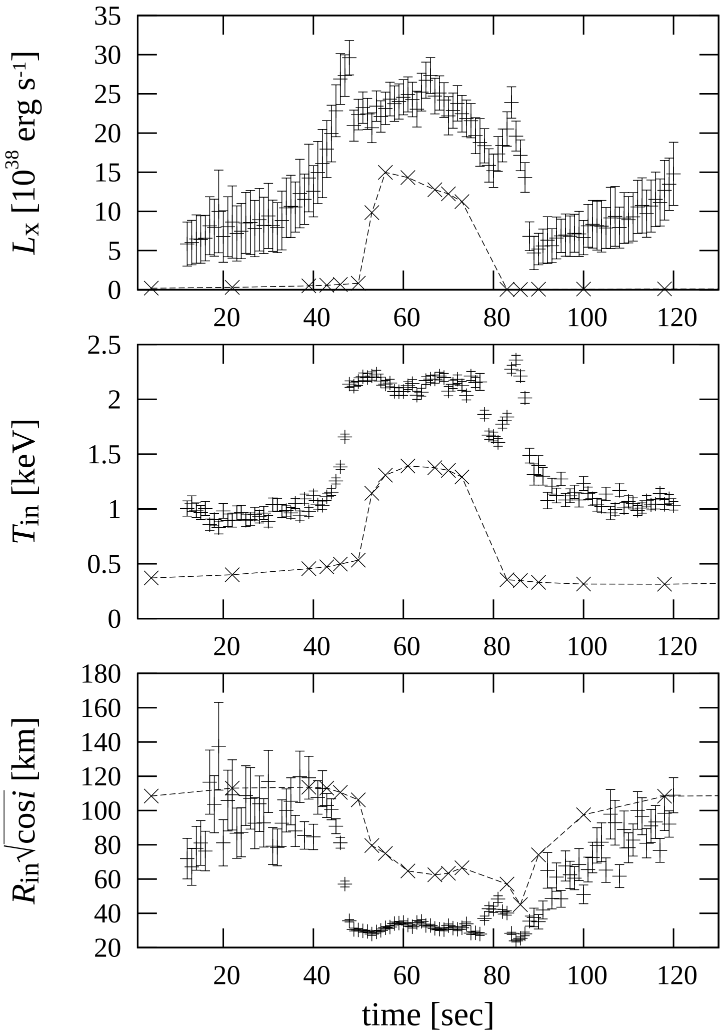

Fig. 4 Bursting behavior of GRS 1915+105. (After Watarai et al. 2003).

time for photons to diffuse in the vertical direction. At sufficiently high rates exceeding $\sim L_E/c^2$, the photon diffusion timescale could be longer than the accretion timescale. What then occurs? Since photons produced inside the disk have no time to reach the disk surface, they are trapped within the flow, carried inward with gas, and finally swallowed by a black hole. As a result, emission efficiency can be considerably reduced. The condition for the critical radius, inside which photon trapping occurs, is written as (Ohsuga, Mineshige & Watarai 2003):

$$r < r_{\rm crit} \equiv (\dot{M}c^2/L_{\rm E})(H/r)r_{\rm S}. \tag{4}$$

Then, what is missing in the slim-disk approach? In the slim disk model, advection of radiation entropy is considered but the radiative loss term is still based on the usual radiative diffusion approximation, $F_{\rm rad} \sim \sigma T^4/\tau$ (see equation 2). In other words, photons are assumed to be immediately go out from the disk surface. But this is not exactly the case once photon trapping occurs. Since there is gas flow with large speed, photon diffusion is not isotropic but shifts inward. We thus need two-dimensional considerations.

Recently, Okuda (2002) computed the two-dimensional radiation hydrodynamical simulation under super-critical mass accretion rate and found that a large amount of outflow/jet via intense radiation pressure are ejected from the disk inner region. This result indicates that we have to consider not only the disk-itself but also the effect of outflow/jet. Hence, the disk-Jet interaction will be one of the important issues in our future works.

4.2 Simple model for photon trapping

We examine the photon trapping effects by solving the radiative diffusion process in the vertical direction within an accreting cell (or a ring), finding an interesting trend in the SED (spectral energy distribution). Within the standard-disk regimes, it is well known that the peak frequency of emergent spectra monotonically increases with increase of $\dot{M}$. When photon trapping becomes significant, in contrast, the peak frequency rather stays constant and then turns to decrease, when $\dot{M}$ increases above critical values of $\sim 10L_{\rm E}/c^2$. This is because high energy photons are mostly generated deep inside the disk (near the equatorial plane) and thus suffer photon trapping effects more effectively than lower-energy photons, which are generated near the surface. As a result, emission of hard photons is more effectively suppressed, yielding a lower shift of the peak energy.

Can we observationally confirm this trend? Unfortunately, we have yet observed such a trend in microquasars, however, but we do observe in the observations of one narrow-line Seyfert 1 galaxy (Haba et al. 2004). The spectral fitting unambiguously shows a decrease of disk temperature as disk luminosity increases. Such a trend cannot be explained by the slim disk model and we think that this is a direct evidence of photon trapping. In addition, there is such an indication that similar behavior seems to be observed in an intermediate-mass black hole, M82 X-1 (Matsumoto et al. 2004).

5 CONCLUSIONS

1. High accretion-rate flows are observed in many different systems. Interaction between radiation and gas is key physics in this regime.
2. GRS 1915+105 seems to probe the presence of transitions between the standard-disk and slim-disk branches.
3. Spectral softening will occur at even higher accretion rates ($> L_{\rm E}/c^2$), because hard photons are more effectively trapped by the flow. We needs more observations.

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