X-ray Fluctuations from the Slim Disk

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Abstract

The responses of perturbations added into the optically thick, advection-dominated accretion disk (ADAD), what we call the slim disk (SD), are investigated through numerical simulations. Although it is proposed that the SD is thermally stable, I find that a perturbation added into the disk is not rapidly damped and moves through the disk in its free-fall time. After the perturbation moves, the global structure of the disk does not vary very much. These facts may account for the substantial variability of the X-ray luminosities of stellar super-luminal jet sources (SLJSs) and Narrow-Line Seyfert 1s (NLS1s).

Key words: accretion disks, black holes

1 Introduction

Recent X-ray observations report that not only stellar black hole candidates (SBHCs) in their low states (=faint sources), but also NLS1s and stellar SLJSs (=bright sources) exhibit X-ray fluctuations (variability). The fluctuations of bright sources are made in the optically thick ADAD, what we call SD (=bright disk). However, the time evolution of the SD has not been investigated so far. The numerical simulation by Manmoto et al. (1996) is well known as a time-evolution calculation of the optically thin ADAD (=faint disk). The disturbance added into the optically thin ADAD falls into the central star. The disk luminosity increases when the disturbance falls, and the light curve of this process is in good agreement with the X-ray shot configuration of the SBHC Cyg X-1 in its low state.

I investigate how the luminosities of disturbed SDs vary. I add a similar disturbance as Manmoto et al. (1996) into the SD, and as a result, a similar light curve to that of the optically thin ADAD is obtained.

The basic equations and numerical procedures are described in §2. The resultant time evolution and discussion will be presented in §3.
Table 1

Parameter sets of Models A–C.

| Model | $r_0$ | $k$ |
|-------|-------|-----|
| A     | 20    | −0.3 |
| B     | 20    | −0.1 |
| C     | 50    | −0.3 |

2 Basic Equations

I calculate the evolution of a one-dimensional axisymmetric disk. The basic equations are the same as those of Manmoto et al. (1996), and are those of mass conservation, momentum conservation, angular momentum conservation, and energy flow:

$$\frac{\partial}{\partial t}(r\Sigma) + \frac{\partial}{\partial r}(r\Sigma v_r) = 0,$$

$$\frac{\partial}{\partial t}(r\Sigma v_r) + \frac{\partial}{\partial r}(r\Sigma v_r^2) = -r\frac{\partial W}{\partial r} + r^2\Sigma(\Omega^2 - \Omega_K^2) - W\frac{d\ln \Omega_K}{d\ln r},$$

$$\frac{\partial}{\partial t}(r^2\Sigma v_\phi) + \frac{\partial}{\partial r}(r^2\Sigma v_\phi v_r) = -\frac{\partial}{\partial r}(r^2\alpha W),$$

and

$$\frac{\partial}{\partial t}(r\Sigma e) + \frac{\partial}{\partial r}(r\Sigma e v_r) = -\frac{\partial}{\partial r}(rWv_r) - \frac{\partial}{\partial r}(r\alpha Wv_\phi) - rF$$

where $\Sigma(= \int \rho dz)$ is the surface density, $W(= \int p dz)$ is the vertically integrated pressure, and $e$ is the internal energy of the accreting gas. $\Omega(= v_\phi/r)$ and $\Omega_K[= (GM/r)^{1/2}/(r-r_S)]$ are the angular frequency of the gas flow and the Keplerian angular frequency in the pseudo-Newtonian potential (Paczyński & Witta 1980), respectively, where $M$ is the mass of the central black hole and $r_S$ is the Schwarzschild radius. I set the viscosity parameter to be $\alpha = 0.1$.

To evaluate the radiative cooling rate, $F$, I consider black body radiation:

$$F = \frac{8acT^4}{3\tau_R/2 + \sqrt{3}},$$

where $a$ is the radiation constant, $T$ is the gas temperature, and $\tau_R$ is the Rosseland optical depth.

I obtain the steady state solution of equations 1–4 and perform the time-evolution calculation using the steady state solution as the initial state. As for
the outer boundary condition, I set all quantities to be those of the standard disk by Shakura & Sunyaev (1973). The inner boundary is set at $r_{\text{in}} = 2.7r_S$, where a free boundary is adopted. I add a mass of $\dot{M}\Delta t$ into the disk through the outer boundary at every time step ($\Delta t$). I set $\dot{M} = 100L_{\text{Edd}}/c^2$ where $L_{\text{Edd}}$ is the Eddington luminosity.

I add a perturbation (disturbance) to the initial state of the disk as

$$\frac{\delta \rho}{\rho} = k \exp \left[ -\left( \frac{r - r_0}{\lambda/2} \right)^2 \right].$$

Throughout these calculations, I assign the wavelength of the perturbation, $\lambda = 20r_S$. I set two parameters, the radius of the center of the perturbation, $r_0$, and the ratio between $\delta \rho$ and $\rho$ at $r = r_0$, $k$. These parameters are varied, with three calculations being performed. The parameter sets of the three calculations are listed in Table 1.

3 Results and Summary

Fig. 1 presents the light curves of Models A–C. All models show shot-like light curves.

Fig. 2 plots how the surface density, $\Sigma$, varies after the perturbation is added for Model A. The dotted and solid lines represent the initial state and the later evolution, respectively. The perturbation does not change its configuration very much, and it does not rapidly decay. The time for the perturbation to propagate corresponds to the free-fall time. After the perturbation has damped, the disk structure is not greatly modified.

The response of SDs to local disturbances has been examined by one-dimensional numerical simulations. It is generally believed that SDs are thermally stable. I, however, find that disturbances added into the accretion flow do not damp rapidly and decay with roughly the free-fall time. After the disturbance has damped, the global disk structure of the disk is not greatly modified. This can account for the persistent X-ray emission with substantial variations observed in NLS1s and SLJSs. When a perturbation is made in the SD, it decays and exhibits one X-ray shot. Since the structure of the SD does not globally vary much after a perturbation propagates, the next perturbation produced in the disk can also exhibit an X-ray shot. Repeating such processes continuously can make the substantial variability seen in the X-ray luminosities of SLJSs and NLS1s.
Fig. 1. Light curves of Models A–C. The solid lines represent the light curves, and the dotted line represents the luminosity in the steady state.

References

[1] T. Manmoto, M. Takeuchi, S. Mineshige, R. Matsumoto, & H. Negoro, ApJ 464 (1996) L135.

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Fig. 2. The time evolution of the disk surface density, $\Sigma$. The dotted and solid lines represent the initial state and the later evolution, respectively. The solid line labeled 1 means the initial configuration of the disturbance. Elapsed times for the labels 2–7 are $t = 397, 785, 1352, 2894, 5997$ and $14288r_S/c$, respectively. Note that both axes represent the relative values.