

# Evolution of Accretion Disks with Mass Evaporation during the Quiescence of WZ Sge-Type Dwarf Novae and X-Ray Novae

Shin MINESHIGE,<sup>1,2</sup> Bifang LIU,<sup>2,3</sup> Friedrich MEYER,<sup>2</sup> and Emmi MEYER-HOFMEISTER<sup>2</sup>

<sup>1</sup>*Department of Astronomy, Kyoto University, Sakyo-ku, Kyoto 606-8502*

*E-mail (SM): minesige@kusastro.kyoto-u.ac.jp*

<sup>2</sup>*Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85740 Garching, Germany*

<sup>3</sup>*Yunnan Observatory, Academia Sinica, P.O. Box 110, Kunming 65011, China*

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## Abstract

We propose a new scenario for disk evolution during the quiescence of WZ Sge-type dwarf novae and X-ray novae. A hole created by evaporation of the inner disk material steadily expands towards larger radii, eventually removing thermally unstable portions of the disk. The disk is, however, not in a steady state, since a certain amount of angular momentum is continuously brought in by an incoming stream, whereas angular-momentum losses due to the evaporation and to the tidal action by a companion star are likely to be small in the quiescence. Accordingly, the total angular momentum of the disk monotonically increases, whereas an increase in the disk mass is somewhat slower because of the mass evaporation. This results in an expansion of the disk and an accumulation of mass in the outermost part of the disk. The quiescence will be terminated if a thermal instability is ignited before the disk expands to the critical radius for the 3:1 resonance between Kepler and orbital angular frequencies. If not, superhumps are expected during quiescence.

**Key words:** Accretion disks — Black holes — Evaporation — Stars: dwarf novae — X-rays: stars

## 1. Introduction

Dwarf novae (DNe) and X-ray novae (XNe, or soft X-ray transients, SXTs) are both close binary systems composed of lobe-filling companion stars and accreting compact objects. Both exhibit similar sporadic outbursts, although the amplitudes, durations, and repetition periods are somewhat larger in XNe than the representative DNe; i.e., U Gem type DNe. There exists, however, an interesting subtype of DNe, called WZ Sge-type stars, which show outbursts rather similar to those of XNe both in amplitudes and timescales. The origin of the peculiar outburst properties of WZ Sge-type stars is still an open question (see Osaki 1998 for comprehensive discussion).

Although the disk-instability model successfully explains the basic outburst properties of dwarf novae (Osaki 1974; a review by Cannizzo 1993) and X-ray novae (e.g., Mineshige, Wheeler 1989), two key questions are addressed. One is the origin of long recurrence times of WZ Sge stars and XNe. It is possible to lengthen repetition cycles by decreasing the viscosity parameter,  $\alpha$  (Smak 1993; Osaki 1995), compared to the usually adopted value,  $\alpha \gtrsim 10^{-2}$  (Cannizzo et al. 1988); however, there still remains the question of why  $\alpha$  is so small, specifi-

cally for these objects. The other is the presence of weak X-ray emission during the quiescence of DNe (see e.g., Beuermann, Thomas 1993) and XNe (McClintock et al. 1995; Narayan et al. 1997). This is difficult to reconcile with the disk-instability model, since it predicts fairly small mass accretion onto compact objects in quiescence.

To resolve this issue, Meyer and Meyer-Hofmeister (1994) proposed the evaporation model for the inner parts of the dwarf-nova disks. Relatively cool gas flowing in from the outer parts is transformed into a hot coronal mass flow in the inner parts. X-rays then originate mainly in a thermal boundary layer at the white-dwarf surface. Simultaneously, UV radiation is produced (la Dous et al. 1997).

Disk evaporation greatly alters the properties of the disk instability in XNe as well (Mineshige 1996). If the inner portions of the standard-type disk, which are thermally unstable in low mass-input systems, evaporate, the disk might become thermally and secularly stable. This idea led Lasota et al. (1995, 1996) to the proposition that long outbursts in WZ Sge stars and XNe are due to a suppression of the disk instability and that outbursts are triggered by mass-transfer bursts. If so, very small  $\alpha$  values would not be necessary for WZ Sge (Hameury et al. 1997; see, however, Warner et al. 1996). They,

however, did not discuss angular-momentum evolution of the disk, which, we emphasize in the present study, is essential when considering the disk evolution in binary systems (Osaki 1989). In sections 2 and 3, we discuss the basic properties of the low-temperature disks suffering mass evaporation and their angular-momentum evolution. A new scenario is proposed in section 4.

## 2. Disk with Mass Evaporation

To begin with, it may be useful to give typical numbers for disks displaying the limit-cycle behavior. For low-temperature disks (with temperature being a few thousand K) the thermal-equilibrium relation between the local stationary mass flow rate,  $\dot{M}$ , and the surface density,  $\Sigma$ , are characterized by the two turning points (or kinks); thus, the equilibrium curves could be S-shaped (Meyer, Meyer-Hofmeister 1981). Here, we denote the upper and lower turning points by A and B, respectively. The corresponding mass-flow rates are (e.g., Mineshige, Osaki 1983)

$$\begin{aligned}\dot{M}_A &\sim 10^{13.6} r_9^{2.6} \left( \frac{M}{M_\odot} \right)^{-0.87} \quad \text{and} \\ \dot{M}_B &\sim 10^{12.8} r_9^{2.6} \left( \frac{M}{M_\odot} \right)^{-0.87},\end{aligned}\quad (1)$$

where  $r_9 \equiv r/(10^9 \text{cm})$  with  $r$  being the distance from the disk center, and  $M$  is the mass of the compact component. It is known that the flow is close to being steady during an outburst. During the quiescence it is non-steady in the sense that the mass-flow rate,  $\dot{M}$ , is an increasing function of  $r$ . Therefore, the surface density  $\Sigma$  steadily increases at every radius according to mass conservation,

$$\frac{\partial \Sigma}{\partial t} = \frac{1}{2\pi r} \frac{\partial \dot{M}}{\partial r} > 0. \quad (2)$$

Figures 1a and b, respectively, illustrate these two critical lines in the  $(\log r, \log \dot{M})$  plane for the cases of DNe (in which  $M = M_\odot$ ) and XNe ( $M = 5 M_\odot$ ). Also drawn are the  $\dot{M}$  distributions during outbursts and quiescence.

Next, we evaluate the mass-evaporation rate. According to Liu et al. (1995), the mass-evaporation rate per unit surface area ( $\dot{m}_0$  in their notation) is approximately given by

$$\dot{\Sigma}_{\text{evp}} \sim 10^{-3.2} r_9^{-3.17} \left( \frac{M}{M_\odot} \right)^{2.34}. \quad (3)$$

The total mass evaporation rate is then roughly given by

$$\dot{M}_{\text{evp}} \simeq \pi r^2 \dot{\Sigma}_{\text{evp}} \sim 10^{15.3} r_9^{-1.17} \left( \frac{M}{M_\odot} \right)^{2.34}. \quad (4)$$

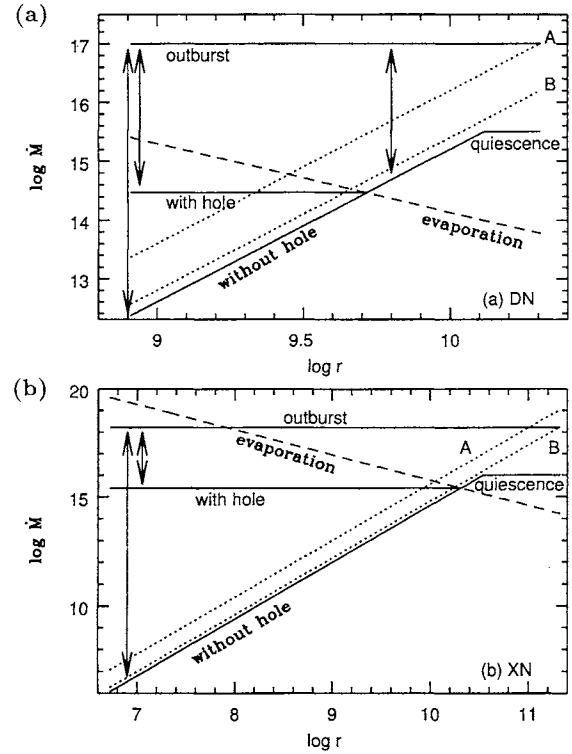


Fig. 1. Mass-flow rates in the disk in dwarf novae (a) and X-ray novae (b), respectively, during the outburst cycle. The short dashed lines indicate the two critical mass-flow rates (A and B), while the long dashed line represents the mass-evaporation rate. During quiescence, the disk lies below the lower critical line, B, if there is no hole. On the other hand, if a hole is created due to mass evaporation, the mass-flow rate is essentially determined by that at the radius where the evaporation rate is equal to the quiescent mass-flow rate in the case without evaporation. At maximum light during an outburst, the entire disk is in a quasi-steady state with a mass-flow rate corresponding to that of point A near to the outer edge of the disk. The mass-inflow rate towards the inner part is thus modulated by several orders of magnitude if there is a hole, whereas the modulation would be much bigger otherwise.

This expression was derived for a one-radial-zone model. A full two-dimensional model might slightly differ in the absolute value for  $\dot{M}_{\text{evp}}$ . However, this rate appears to agree with the observations for VW Hyi, assuming a white-dwarf mass of  $1 M_\odot$  (Meyer, Meyer-Hofmeister 1994). In figures 1a and b, the long dashed lines show the mass-evaporation rates as functions of the radii. Inside the truncation radius, where  $\dot{M}_{\text{evp}} \sim \dot{M}_B$ , cool disk material is likely to be completely evaporated into a coronal flow. Thus, if there is a hole due to mass evaporation, the mass-flow rate through the inner, coronal parts

is spatially constant with the value being equal to that at the truncation radius. (Note that a ‘hole’ used here does not mean an empty space but is filled with a hot tenuous coronal flow.) The evaporation of a DN disk was computed in detail by Liu et al. (1997). The difference between the cases with and without a hole is more significant for large  $M$  systems; i.e., XNe. This gives rise to a large difference, by more than 10 orders of magnitude, in the mass-flow rate near to compact objects, and thus in X-ray intensities during quiescence (Mineshige 1996).

There are several reasons why very small  $\alpha$  values were required in previous studies (see Osaki 1998 and references therein). First of all, the duration of the quiescence is basically determined by the viscous timescale in the cool state, which is roughly [equation (7) of Osaki 1995, see also Smak 1993]

$$\tau_Q \simeq 1(\text{yr}) \left( \frac{\alpha}{0.01} \right)^{-1} \left( \frac{r_d}{10^{10} \text{cm}} \right)^{1/2} \times \left( \frac{T_{\text{cool}}}{4000 \text{ K}} \right)^{-1} \left( \frac{M}{M_\odot} \right)^{1/2}, \quad (5)$$

where  $r_d$  is the size of the disk. (It is assumed here that the duration of quiescence is determined by the viscous timescale at the outer rim.) Obviously, for  $M \sim M_\odot$ ,  $r_d \lesssim 2 \times 10^{10} \text{cm}$ , and  $\tau_Q > 30 \text{ yr}$  we need to assign  $\alpha < 10^{-3}$ .

The second argument is based on an evaluation of  $\Delta M$ , the mass released during a burst. If gas is added to the disk from the companion star at a constant rate  $\dot{M}_{\text{inp}}$ , and if there is no mass evaporation, the total accumulated mass during quiescence is

$$\Delta M = \dot{M}_{\text{inp}} \tau_Q \sim 10^{15} (\text{g s}^{-1}) \times 30 (\text{yr}) = 10^{24} (\text{g}). \quad (6)$$

Such a large mass is also required to produce large-amplitude outbursts of WZ Sge, as are observed (Osaki 1995). Since a thermal instability should not be triggered during quiescence, we require that the surface density is everywhere below its critical value,  $\Sigma_B$ , over which an instability sets out,

$$\Sigma < \Sigma_B \simeq 10^{2.5} (\text{g cm}^{-2}) \left( \frac{\alpha}{0.01} \right)^{-0.8} r_{10}^{1.05} \left( \frac{M}{M_\odot} \right)^{-0.35}. \quad (7)$$

We, thus, find the upper limit to the disk mass stored in the quiescence to be

$$\begin{aligned} \Delta M &< \int_0^{r_d} 2\pi r \Sigma_B dr = \frac{2\pi r_d^2 \Sigma_B}{3.05} \\ &\simeq 10^{22.8} (\text{g}) \left( \frac{\alpha}{0.01} \right)^{-0.8} \left( \frac{r_d}{10^{10} \text{cm}} \right)^{3.05} \left( \frac{M}{M_\odot} \right)^{-0.35}. \end{aligned} \quad (8)$$

For smaller  $\alpha$  values we can store a larger mass without igniting a thermal instability. Since  $\Delta M \sim 10^{24} \text{g}$

[equation (6)], we find  $\alpha < 10^{-3}$  for  $M \sim 1 M_\odot$  and  $r_d \sim 10^{10} \text{cm}$  (the case of DNe). If disk evaporation is efficient, however,  $\Delta M < \dot{M} \tau_Q$ , thus allowing a slightly larger  $\alpha$ . In addition, if we take  $r_d \sim 2 \times 10^{10} \text{cm}$ , which is the critical radius for the 3:1 resonance for WZ Sge (Osaki 1989), even larger  $\alpha$  values ( $\sim 0.01$ ) are admissible. We will demonstrate that this seems to actually be the case for WZ Sge in next section. Note that the constraint is not very severe for XNe, which have larger disk sizes of  $\sim 10^{11} \text{cm}$ .

### 3. Angular-Momentum Evolution during Quiescence

We consider here the significance of the angular-momentum evolution of the disk, which was not properly considered in Lasota et al. (1995). Even if the mass-input rate into the disk is balanced by the mass-accretion rate out of the disk, it is too early to conclude that the disk is steady, since the angular-momentum balance may not hold. Following Osaki (1989), we write the mass and angular-momentum conservations as

$$\begin{aligned} \frac{dM_d}{dt} &= \dot{M}_{\text{inp}} - \dot{M}_{\text{acc}}, \\ \frac{dJ_d}{dt} &= j_{\text{inp}} \dot{M}_{\text{inp}} - j_{\text{acc}} \dot{M}_{\text{acc}} - \dot{J}_{\text{tidal}}. \end{aligned} \quad (9)$$

Here,  $\dot{M}_{\text{inp}}$  and  $\dot{M}_{\text{acc}}$  represent the mass input rate into the disk and the mass accretion rate onto the central object, respectively;  $j_{\text{inp}}$  and  $j_{\text{acc}}$  are the specific angular momentum brought in by the gas stream from the companion star and that carried away by accreting material, respectively; and  $\dot{J}_{\text{tidal}}$  represents the angular-momentum removal rate due to the tidal action by the companion star.

If there is no thermal instability, we set  $\dot{M}_{\text{inp}} = \dot{M}_{\text{acc}}$ ; therefore,

$$\frac{dM_d}{dt} = \dot{M}_{\text{inp}} - \dot{M}_{\text{acc}} = 0. \quad (10)$$

As a result, the total disk mass does not change. Nevertheless, the total angular momentum should change. Since in the long-term average (average over one outburst cycle) the angular momentum should be conserved,

$$\begin{aligned} 0 &= \oint \left( j_{\text{inp}} \dot{M}_{\text{inp}} - j_{\text{acc}} \dot{M}_{\text{acc}} - \dot{J}_{\text{tidal}} \right) dt \\ &\simeq \oint \left( j_{\text{inp}} \dot{M}_{\text{inp}} - \dot{J}_{\text{tidal}} \right) dt. \end{aligned} \quad (11)$$

Now  $\dot{J}_{\text{tidal}}$  is greatly enhanced during superoutbursts, in which superhump light variations are observed (Osaki 1989). Therefore,  $\dot{J}_{\text{tidal}}$  should be of minor importance compared with  $j_{\text{inp}} \dot{M}_{\text{inp}}$  during quiescence; that is,

$$\frac{dJ_d}{dt} = (j_{\text{inp}} - j_{\text{acc}}) \dot{M}_{\text{inp}} - \dot{J}_{\text{tidal}}$$

Table 1. Mass and angular momentum in various stages.

Stage	$\dot{M}_{\text{inp}}$ and $\dot{M}_{\text{acc}}$	$M_d$	$\dot{J}_{\text{inp}}$ and $\dot{J}_{\text{tidal}}$	$J_d$	$J_d/M_d$	$r_d$
steady state.....	$\dot{M}_{\text{inp}} = \dot{M}_{\text{acc}}$	$\rightarrow$	$\dot{J}_{\text{inp}} = \dot{J}_{\text{tidal}}$	$\rightarrow$	$\rightarrow$	$\rightarrow$
quiescence without hole.....	$\dot{M}_{\text{inp}} \gg \dot{M}_{\text{acc}}$	$\nearrow$	$\dot{J}_{\text{inp}} \gg \dot{J}_{\text{tidal}}$	$\nearrow$	$\searrow$	$\searrow$
outburst.....	$\dot{M}_{\text{inp}} \ll \dot{M}_{\text{acc}}$	$\searrow$	$\dot{J}_{\text{inp}} \ll \dot{J}_{\text{tidal}}$	$\searrow$	$\nearrow$	$\nearrow$
quiescence with hole.....	$\dot{M}_{\text{inp}} = \dot{M}_{\text{acc}}$	$\rightarrow$	$\dot{J}_{\text{inp}} \gg \dot{J}_{\text{tidal}}$	$\nearrow$	$\nearrow$	$\nearrow$

\*  $\dot{J}_{\text{inp}} \equiv \dot{M}_{\text{inp}} j_{\text{inp}}$ .

$$\simeq j_{\text{inp}} \dot{M}_{\text{inp}} - \dot{J}_{\text{tidal}} > 0. \quad (12)$$

To summarize,  $J_d$  steadily increases, whereas  $M_d$  increases more slowly because of evaporation. Thus, the mean angular momentum,  $J_d/M_d$ , increases. Since the specific angular momentum [ $j(r) = \sqrt{GM}r \propto r^{1/2}$ ] is a function of only the radius, an increase in the mean angular momentum results in mass accumulation in the outermost parts and/or expansion of the disk. Expansion of the disk size towards the outburst phase is consistent with neglecting the tidal effects,  $\dot{J}_{\text{tidal}}$ , during quiescence (recall that the tidal torque is a very sensitive function of  $r$ ; e.g., Smak 1984).

The effects of mass evaporation are thus twofold: a continuous loss of the disk mass and a secular increase in the total angular momenta; monotonic disk expansion is thus an inevitable consequence (see table 1). The disk cannot stay as it is at the beginning of quiescence. Strictly speaking, however, the total mass should increase to some degree during quiescence, since otherwise there would be no mass storage used for outbursts.

For the usual type quiescent disk, equation (5) gives a good estimate of the quiescent period. The quiescent period could be much longer, if, as in the model by Warner et al. (1996), the disk is almost in a steady state in the sense that the mass supply from the secondary star is almost in balance with the mass loss from the inner edge (a leaky bucket model; see Osaki 1998). In the case that the disk is steadily expanding with the time, the quiescent period could also be longer, since it then takes time to pile up disk material outside the disk radius at the beginning of quiescence. For a more quantitative discussion, however, we need numerical calculations (see Meyer-Hofmeister et al. 1998).

#### 4. New Scenario for Quiescent Disk Evolution

Since the disk is not steady even if a hole removes the unstable portions of the disk, there is a chance for the disk to become unstable. We thus have two possible scenarios for the ignition of disk instabilities. The first one is similar to the original model by Osaki (1989). Even if the disk expansion tends to distribute disk material

specifically to the outer portions, where the critical  $\Sigma_B$  is larger, since the critical surface density will eventually be reached, a thermal instability will be ignited. This would cause a rapid mass-accretion flow, resulting in rapid disk expansion. When the disk expands up to the critical radius for 3:1 resonance, a tidal instability sets out and produces superhump light variations.

We, however, have an alternative, quite new scenario. If the expansion of the disk is sufficiently rapid, the outer edge of the disk reaches the critical radius before  $\Sigma$  exceeds  $\Sigma_B$  somewhere within the disk. Then, a tidal instability sets out at first. This tidal dissipation might be thought to trigger an outburst. It is however only on the order of magnitude as that in the hot spot where the overflowing mass stream impinges on the disk, and therefore probably not effective enough, like the hot spot.

Once the disk has reached the resonance radius it can remove all of the angular momentum from the accretion by the tidal force, and therefore it does not grow further. Then mass storage by disk growth ends and all of the transferred mass now flows inward through the disk. This sudden increase in the disk mass flow increases the disk surface density, and can then lead to triggering of an outburst when the critical surface density is reached. If even this increase in the disk mass flow does not lead to outburst triggering, the system becomes a steady quiescent accretion and a member of the “graveyard” of never outbursting old CVs (Meyer-Hofmeister et al. 1998). The system becomes a kind of “permanent superhumper” during quiescence.

It is interesting to note, in this respect, that Kato et al. (1998) observed the persistent superhump variations indicative of the onset of a tidal instability, even during the quiescent periods between the repetitive short outbursts after the 1997 outburst of the WZ Sge-type dwarf nova EG Cnc. This strongly indicates that a tidal instability can take place without invoking a thermal instability. More theoretical and observational investigations are needed in this field.

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