

**On the Role of Irradiation and Evaporation in Strongly Irradiated
Accretion Disks in the Black Hole X-ray Binaries: Toward an
Understanding of FREDs and Secondary Maxima**

John K. Cannizzo¹

e-mail: cannizzo@stars.gsfc.nasa.gov

NASA/GSFC/Laboratory for High Energy Astrophysics, Code 662, Greenbelt, MD 20771

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¹ Universities Space Research Association

ABSTRACT

We examine a new paradigm to account for the exponential decay seen in the light curves of some of the bright X-ray novae. These systems show an exponential decay in soft X-rays with an e -folding time constant of ~ 30 d. We investigate a scenario in which evaporation of matter into a corona is the dominant mass removal mechanism from the accretion disk. We utilize the thermal evaporative instability discovered by Shaviv and Wehrse. First we parametrize local mass loss rates from the disk (fitted to vertical structure computations of the optically thin structure using the photoionization code CLOUDY), and then we utilize the scalings in our numerical time dependent model for the decay. Both the ~ 30 d e -folding time scale for the decay and the secondary maximum with its rapid rise time $\sim 1 - 3$ d which is seen in the X-ray nova light curves can be produced by adjusting the strength of the evaporation.

Subject headings: accretion, accretion disks – black hole physics – transients:
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1. INTRODUCTION

The accretion disk limit cycle model has been successful in explaining the outbursts seen in dwarf novae and X-ray transients (see Cannizzo 1993a, 1998, and references therein; Hameury et al. 1998). In several of the brightest and best studied X-ray novae one sees a rapid rise to maximum light, followed by an exponential decline. The time constant associated with the decline is $\sim 30 - 40$ d (Mineshige et al. 1993, Chen et al. 1997). In addition, one also sees a secondary maximum ~ 50 d after the initial maximum, during which time the X-ray flux increases by a factor $\sim 1.5 - 2$ before resuming its exponential decay. The post-secondary maximum light curve is therefore parallel to (but offset from) the pre-secondary maximum light curve when plotted as $\log L_X$ versus time.

The X-ray novae are thought to consist of interacting binaries in which a mass losing late-type star transfers matter onto a black hole (BH) (Tanaka & Shibazaki 1996). If we adopt the canonical wisdom that the X-ray flux seen in the outbursts is due to accretion from a transient accretion disk, then logic would dictate that the reason for the decline in X-ray flux is a decline in the mass of the accretion disk. The question then arises as to where the dominant mass removal occurs. Three natural possibilities present themselves for removing gas from the viscously active inner disk: (1) outflow at the outer edge due to thermal instability, (2) standard viscous accretion onto the BH, and (3) evaporation of gas from the surface of the disk.

1. mass removal from the outer disk edge: Cannizzo et al. (1995) proposed that the exponential decays are due to the action of a cooling front in the disk. A cooling front in the limit cycle model (Cannizzo 1993a) invariably begins at large radii in the accretion disk and moves to smaller radii, producing a vigorous outflow at the hot/cold interface that is several times as large as the rate of accretion onto the central object from the inner disk (Vishniac & Wheeler 1996, Vishniac 1997; Menou, Hameury, & Stehle 1999).

For this scenario to be workable in the context of the X-ray novae, however, the viscosity parameter for ionized gas α_{hot} must have the form $\alpha_{\text{hot}} \simeq \alpha_0 (h/r)^n$, where $\alpha_0 \simeq 50$ and $n \simeq 1.5$. There are several problems with this. First, in the outbursting dwarf novae we infer $\alpha_{\text{hot}} \simeq 0.1$ from the Bailey relation between decay time and orbital period (Smak 1984, 1999), therefore one would have to invoke a special form for α_{hot} in the X-ray novae. (The value $\alpha_{\text{hot}} \simeq 0.1$ exceeds by a nominal factor estimates taken from three-dimensional MHD calculations of the nonlinear saturation limit for the Balbus-Hawley instability, the currently favored model for generating viscous dissipation from the Keplerian shear in accretion disks [Stone et al. 1996, Fleming et al. 2000]). Second, the strong irradiation in outbursting X-ray novae should prevent the cooling front from forming. If as little as $\sim 10^{-3} - 10^{-4}$ of the central X-ray flux is received by the accretion disk via indirect scattering, the locally defined irradiation temperature would exceed $\sim 10^4$ K at the outer disk edge, which would be sufficient to keep the whole disk ionized.

2. mass removal from the inner disk edge: It has been known for some time that irradiation is a much stronger physical effect in the LMXBs than in the cataclysmic variables (van Paradijs & Verbunt 1984, van Paradijs 1996). As just noted, strong irradiation of the outer portions of the accretion disk by X-ray flux coming from the inner disk edge will tend to keep the disk in a hot, ionized state, and prevent a cooling front from forming (Tuchman et al. 1990, Mineshige et al. 1990). In this case the decay rate will be slower, for a given α law, insofar as viscous processes operate on a longer time scale than thermal processes. King & Ritter (1998, see also King 1998, Shahbaz et al. 1998) argue for a viscous decline to account for the ~ 30 d e -folding decays in the X-ray novae, because one does not expect a cooling front to be present. This scenario is not without difficulties, however. If we assume that $\alpha_{\text{hot}} \simeq 0.1$ as for outbursting dwarf nova disks, then for an accretion disk with an outer radius $r_{\text{outer}} \approx 10^{11}$ cm relevant for A0620-00, for example, the locally defined e -folding decay time in the X-ray light curve would be ~ 300 d – about a factor of ten

slower than observed. In addition, Kaluzienski et al. (1977) report a slight increase in the rate of decay of the 1975 outburst of A0620-00 during the later stages of the outburst. They fit an e -folding decay time scale of ~ 29 d to the pre-secondary maximum light curve, and a decay time of ~ 21 d to the post-secondary maximum light curve. A viscous decay would produce the opposite effect – an increase in the viscous time scale due to decreased mass in the disk as the outburst proceeds. This comes about because the viscous time scale $\tau_v = [\alpha\Omega(c_s/r\Omega)^2]^{-1}$ varies as the reciprocal of the midplane temperature T_{midplane} ($\propto c_s^2$), and as the disk drains onto the BH, the surface densities and concomitant midplane temperatures diminish.

3. mass removal from intermediate radii: Shaviv & Wehrse (1986, hereafter SW86) discovered an evaporative instability associated with the local minimum in the pressure in the optically thin vertical structure of an accretion disk overlying the photosphere. Recently de Kool & Wickramasinghe (1999, hereafter dKW) computed the amplitude of this effect for both non-irradiated systems (dwarf novae) and strongly irradiated systems (X-ray novae). They found that evaporation can be dominant for the latter systems. dKW present a simple formalism for using a photoionization code to calculate the vertical structure. We note that other physical mechanisms have been discussed for removing disk material in the form of a wind – for instance the “coronal siphon flow” (Liu, Meyer, & Meyer-Hofmeister 1995, 1997). In this work we utilize the SW86 mechanism because it is conceptually straightforward and one can readily quantify its strength in simple vertical structure calculations. Many previous workers have considered strongly irradiated disks (e.g. Begelman et al. 1983; Ko & Kallman 1991; Raymond 1993; Hameury et al. 1997, Dubus et al. 1999, Menou et al. 2000).

We perform vertical structure calculations using the photoionization code CLOUDY (Ferland 1996) for an accretion disk around a $10M_{\odot}$ black hole, and parametrize conditions

at the local minima in pressure – the point at which hydrostatic equilibrium can no longer be maintained. The local outflow rate in a given annulus is expressed in terms of power law scalings in r and \dot{M} , and these are then utilized in our global time dependent computations to calculate light curves based on the rate of accretion onto the central object, and the V band flux from the accretion disk.

2. MODEL CALCULATIONS

As in dKW, we simply set the heating and cooling rates to be equal in the photoionization code. The heating has two sources: X-ray irradiation from accretion onto the central object, and local viscous dissipation. The first term is by far the dominant one in this work. Cooling occurs through a variety of physical processes calculated by CLOUDY. Our method is the same as that described in Section 4.2 of dKW (except that we use CLOUDY rather than MAPPINGS). The heating rate per unit volume is $1.5\alpha\Omega P_g$, where $\alpha_{\text{chromosphere}} = 0.3$, Ω is the local Keplerian angular velocity, and P_g is the gas pressure. The irradiation heating comes via a dilute radiation field, $T_{bb} = T_{\text{d,eff}}(r_{\text{max}})$, where $T_{\text{d,eff}}$ is the effective temperature given by $\sigma T_{\text{d,eff}}^4 = (3/(8\pi))\Omega^2\dot{M}$ (Shakura & Sunyaev 1973), and r_{max} is the radius where most of the energy is dissipated. The radiation field is diluted by a geometric factor $\eta r_{\text{max}}^2/(4r^2)$, where $\eta = 0.1$, and $r_{\text{max}} = 10^7$ cm. Thus we assume the irradiation to be indirect rather than direct. For BH parameters, the photosphere of the accretion disk is irradiation-dominated at all radii (see eqn. [3] of Ko & Kallman 1991).

Figure 1 shows the vertical structure of the optically thin part of the accretion disk overlying the photosphere of an optically thick disk for five values of \dot{M} , at one representative radius in the disk. For the three lowest \dot{M} curves in the first panel one can see a local minimum in the pressure. The third panel shows $2\pi r^2 \rho c_s^2$. The value of this

quantity evaluated at the minimum in pressure estimates the local outflow (Czerny & King 1989). We utilize power law scalings of these minima (as functions of r and \dot{M}) in our time dependent computations to calculate the local mass loss rates. In our time dependent model, we take the local mass loss rate from a given annulus $\Delta\dot{M}(r)$ to be $4\pi r\Delta r\rho c_s^2$. Our scaling based on the CLOUDY results is $\Delta\dot{M}(r) = 2A\Delta r/r$, where A is the local wind loss rate parametrization as considered by dKW and shown in Fig. 1, namely $2\pi r^2\rho c_s^2$ which we approximate as $10^{17} \text{ g s}^{-1} \dot{M}_{c,18}^{1/4}$. The quantity $\dot{M}_{c,18}$ is the rate of mass loss from the inner accretion disk onto the BH in units of 10^{18} g s^{-1} . One caveat to note: CLOUDY is not intended to be accurate for densities significantly above about $10^{-10} \text{ g cm}^{-3}$. Although the densities corresponding to the minima in P_{gas} for the specific radius $10^{9.5} \text{ cm}$ shown in Fig. 1 are less than this, disk densities generally increase with decreasing radius, so that for smaller radii our scaling for $\Delta\dot{M}(r)$ may begin to break down. In this inner disk region other deficiencies in our time dependent model connected with our neglect of general relativistic effects such as transonic flow also become manifest. We plan to account for these effects more fully in future work. Another caveat is our assumption that a constant fraction of the indirect irradiation is received by the disk as the outburst fades, which we make for simplicity. A multidimensional treatment would be required in order to make a more self-consistent model. Finally, we cannot address the ultimate (nonlinear) fate of the gas lost in the wind. In this work we simply assume that it becomes added to a static corona which is dynamically decoupled from the underlying accretion disk.

The time dependent code we utilize to follow the accretion disk evolution is a modification of one described extensively in earlier works (Cannizzo 1993b, Cannizzo et al. 1995, Cannizzo 1998). The two modifications in this work are that (1) we allow for the effects of indirect irradiation, using the form cited earlier. The effect of irradiation on the steady state solutions was taken from Tuchman et al. (1990). (2) We also remove matter at each annulus in accord with the aforementioned $\Delta\dot{M}(r)$ prescription. All aspects

of the code which involve thermal transition fronts are not utilized in this work, because irradiation prevents the cooling front from forming and keeps the entire disk in the ionized state. We assume a central BH mass of $10M_{\odot}$, and we distribute 1000 grid points equally spaced in \sqrt{r} between $r_{\text{inner}} = 10^7$ cm and $r_{\text{outer}} = 1.5 \times 10^{11}$ cm.

The effect on the evolution of the disk is quite pronounced. Figures 2 and 3 show the time dependent accretion disk evolution both with and without evaporation. A purely viscous decay with $\alpha_{\text{hot}} = 0.1$ and disk parameters appropriate for A0620-00 gives a slower-than-exponential decay, with a decay time constant $\tau_e \approx 300$ d. The solid line in Fig. 2 reveals the exponential character of the decay if one has weak evaporation. In this model we reduce the amplitude of the evaporation calculated from the CLOUDY models by a factor of 30. The time constant for the decay of \dot{M}_{inner} which powers the soft X-ray flux in this model is $\tau_e \approx 80 - 100$ d. Fig. 3 shows the case for stronger evaporation – for which the amplitude of the evaporation calculated from the CLOUDY models is only reduced by a factor of 10 – so that $\tau_e \approx 20 - 30$ d. One now sees a secondary maximum in the light curve of \dot{M}_{inner} corresponding to the evacuation of the innermost disk, and its subsequent refilling. The rapid rise time for the secondary maximum is a natural artifact of the fast viscous time at $\sim 10^8 - 10^9$ cm. The entire accretion disk is not able to re-adjust quasi-statically to the persistent mass loss. The viscous time scale, which is equivalent to the time scale for the surface density to adjust to strong perturbations, is initially $\tau_v \simeq 10^6$ s $(r/10^{10} \text{ cm})^{1.25}$ in our calculations, whereas the mass loss time scale $\tau_{\dot{M}}$ has about the same form but is roughly 30 times slower (in our “optimal” model). As evaporation proceeds near the inner edge, however, $\tau_v(r_{\text{inner}})$ increases more rapidly than $\tau_{\dot{M}}(r_{\text{inner}})$, and at some point $\tau_{\dot{M}} < \tau_v$ so that evaporation wins.

3. DISCUSSION AND CONCLUSION

We have examined the decay from outburst in X-ray novae both with and without evaporation of the inner disk. In our model with $\alpha_{\text{hot}} = 0.1$ (as inferred from dwarf novae), the decay time τ_e varies from ~ 260 d to ~ 340 d over the 250 d time span of our run. This time scale is about a factor 10 slower than observed, and would be expected in the scenario of King & Ritter (1998) in which the disk is held in the hot, ionized state by strong irradiation expected in a soft X-ray transient. Increasing α_{hot} to 1 reduces the time scale τ_e associated with mass loss onto the central BH, but also increases the deviation from exponentiality: over the 250 d of the model, the e -folding time scale associated with the decrease in \dot{M}_{inner} varies from ~ 40 d to ~ 120 d. Observations also exclude this model. For models including evaporation during outburst, where the evaporation is parametrized using steady state computations of the Shaviv & Wehrse instability, evaporation is dominant over the viscous evolution in the sense that the rate of removal of material from the inner disk leads to an e -folding decay rate associated with the loss of material from the inner accretion disk which is $\gtrsim 10$ times faster than that due to viscous evolution alone. More importantly, the decline maintains an exponential shape over $\gtrsim 2$ orders of magnitude in \dot{M}_{inner} .

An unexpected consequence of the depletion of matter from small radii in the disk is the effect of the evacuation and subsequent refilling of material in the innermost disk. This produces a small increase in \dot{M}_{inner} , followed by the resumption of a rate of decrease equal to what it had been earlier, which seems to account naturally for the secondary maxima. The time constant associated with the post-secondary maximum decay for the run shown in Fig. 3 is actually slightly less than that associated with the pre-secondary maximum decay, as was observed in the 1975 outburst of A0620-00 (see Fig. 1 of Kaluzienski et al. 1977). Also, the fast rise time of $\sim 1 - 3$ d for the secondary maximum in our model represents the viscous evolution time at small radii $\sim 10^8$ cm in the disk. By contrast, the previous models of the secondary maxima by Chen et al. (1993) and Augusteijn et al. (1993) which invoke

the addition of extra material from the secondary would give very slow secondary maxima with rise times of ~ 1 yr, because the matter added to the outer disk at $\sim 10^{11}$ cm would require a long time to enhance the accretion rate at small radii where X-rays are produced. Another point of consistency with observations in our model for the secondary maximum is that, insofar as its root cause is a readjustment of the surface density distribution in the inner disk, the impact on the V light curve is minimal. The V band flux is heavily weighted by contributions from the outer disk radii (Cannizzo 1996), and therefore it responds on a much longer time scale to processes occurring at the inner edge – effectively smearing out their effects.

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FIGURE CAPTIONS

Figure 1. The vertical structure of the optically thin part of the accretion disk overlying the photosphere. The input parameters are $M_1 = 10M_\odot$, $r = 10^{9.5}$ cm, and $\alpha_{\text{chromosphere}} = 0.3$. Five curves are shown, for $\dot{M} = 10^{14.5}$ g s $^{-1}$ through $\dot{M} = 10^{18.5}$ g s $^{-1}$ in steps of 1.0 dex. Shown are the logarithms of gas pressure P_{gas} (*top panel*), density ρ (*middle panel*), and $2\pi r^2 \rho c_s$ (*bottom panel*) which has units of g s $^{-1}$ and provides a measure of the expected outflow in regions where hydrostatic equilibrium cannot be maintained (Czerny & King 1989).

Figure 2. The time dependent evolution of the accretion disk both with and without evaporation. Shown are the absolute V mag for a face-on disk (*top panel*), the mass of the disk in units of 10^{25} g (*second panel*), the logarithm of the rate of mass removal from the inner disk edge in g s $^{-1}$ (*third panel*), and the locally defined e -folding decay time τ_e for $(dm/dt)_i$ (*bottom panel*). The three curves shown represent runs for (i) a viscous decay with $\alpha_{\text{hot}} = 0.1$ (*dotted curve*), (ii) a viscous decay with $\alpha_{\text{hot}} = 1$, (*dashed curve*), and (iii) a viscous plus (weak) evaporative decay with $\alpha_{\text{hot}} = 0.1$ (*solid curve*), where the strength of the evaporation has been reduced by 30 from what was computed using CLOUDY and shown in Fig. 1. For these runs no cooling front is present because of the strong irradiation. For the viscous decay run with $\alpha_{\text{hot}} = 0.1$, the associated decay time constant τ_e varies from ~ 260 d to ~ 340 d, whereas in the run for $\alpha_{\text{hot}} = 1$, τ_e increases from ~ 40 d to ~ 120 d over the period of evolution shown. In the model with weak evaporation a closely exponential decay with $\tau_e \simeq 80 - 100$ d results.

Figure 3. The evolution of the accretion disk with stronger evaporation than what was shown in Fig. 2. The four panels are the same as in Fig. 2. For this run we reduce the strength of the evaporation by a factor of 10 from what was computed using CLOUDY and shown in Fig. 1, resulting in a decay with $\tau_e \simeq 20 - 30$ d. By $t = 100$ d the inner disk has

evaporated, and material from further out in the disk flows inward to fill the cavity. The post-secondary maximum decay is exponential also, with a slightly faster time constant than before.





