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The Evolution of the Optically Thick Accretion Disk in Nova Muscae

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ABSTRACT

We here model the soft X-ray flux from the black hole X-ray nova, GS 1124-68 (Nova Muscae, GRS 1124-68) as emission from an optically-thick accretion disk with Comptonization. Our results suggest that the disk's inner edge has a radius whose dependence on the accretion rate is a power-law, and that the slope of this function changes between the different spectral states. This disk configuration retains a hot inner region, which can account for the hard X-rays, though its structure appears to be different during the soft and ultra-soft states.

Subject headings: accretion disks—black hole physics—radiation mechanisms: thermal—relativity—stars: Cygnus X-1

1. Introduction

The bright X-ray nova, Nova Muscae (GS 1124-68, GRS 1124-68) was detected on January 8, 1991 by both the */it* Ginga and */it* GRANAT satellites (Lund 1991; Ebisawa et al. 1994; Goldworm et al. 1993). Subsequent optical photometry and spectroscopy (Remillard et al. 1992) revealed that its mass function is $3.1 \pm 0.4 M_{\odot}$, establishing that this source is a black hole candidate.

Nova Muscae's spectral evolution was quite similar to that of other black hole X-ray novae. Its soft X-ray emission (Ebisawa et al. 1994) increased from around Jan 8, 1991 onwards and peaked in about 10 days, after which the luminosity decayed with an e-folding time of about 30 days. A secondary peak appeared in the soft X-rays roughly 70 days after the outburst when the emissivity increased by a factor of 2 before continuing to decay at the earlier rate. The soft X-rays dominated the bolometric luminosity over the first 120 day period, during which the hard X-ray power-law contributed less than $\approx 40\%$ of the total power in the first 50 days (ultra soft-state) and $\lesssim 10\%$ near the secondary maximum of the soft X-ray light curve (soft-state). However, the hard component was dominant (at the $\approx 80\%$ level) 140 days after the outburst, giving rise to the hard state.

Ebisawa et al. (1994) fitted the soft X-ray flux using a multi-color disk model, assuming that the ratio of the color to effective temperatures of the disk was independent of both radius and accretion rate $\dot{M}$. This assumption is valid when the hot electrons on the disk surface Comptonize the emergent spectrum (Shimura & Takahara 1995; Ross, Fabian & Mineshige 1992). They concluded that the inner radius of the optically thick disk does not vary significantly with $\dot{M}$, implying that it extends down to the last stable orbit during the entire evolution of the nova. This result is interesting because it contrasts with the prediction of several accretion disk models (Shapiro, Lightman & Eardley 1976; Narayan & Yi 1995; Ebisawa, Titarchuk & Chakrabarti 1996; Misra & Meia 1996a), in which the inner disk region becomes hot and emits the observed hard X-rays. The Paradox arises because the hard X-rays emitted during the ultra soft state indicate that such a hot region is probably present.

In this paper, we inspect the data more closely and demonstrate that examining the disk's radial dependence on $\dot{M}$ separately in the various spectral states does in fact allow for a variation in the location of the disk's inner edge. By extension, we infer the presence of a hot inner region, which can account for the hard component and thus produce better consistency with some of the models. We show, moreover, that the accretion rate does not appear to be a direct measure of the total luminosity. This implies that a certain fraction of the released gravitational energy is probably advected inwards through the event horizon. We shall describe the disk's evolution in the following section, and then present our results, mostly in graphical form, in section 3.

2. The Optically Thick Disk Evolution

The gravitational energy released per second in the optically thick portion of an accretion disk is $L = (3/2)(GM\dot{M}/R_i)J_2(R_i)$, where M is the mass of the black hole, $\dot{M}$ is the accretion rate and R_i is the inner radius of the optically thick disk. The function $J_2(R_i) \equiv 1 - (2/3)(R_*/R_i)^{1/2}$, takes into account the boundary condition at the inner disk radius R_* . For a non-rotating black hole, $R_* = 3r_g$, where $r_g \equiv 2GM/c^2$ is the Schwarzschild radius. Thus the flux observed at earth is,

$$F_e = \frac{3}{4\pi} \frac{GM\dot{M}}{R_i} \frac{\mu}{D^2} J_2(R_i), \quad (1)$$

where $\mu = \cos(i)$ is the cosine of the inclination angle i and D is the distance to the source.

The hot electrons in the upper layer of an optically thick accretion disk can modify the emergent spectrum by Comptonization (e.g., Shimura & Takahara 1995; Ross, Fabian & Mineshige 1992). This process is important when the y parameter is greater than one. When absorption is also important, the y parameter is frequency dependent and is given by (Rybicki & Lightman Eq. 7.42),

$$y \approx \frac{4kT}{m\epsilon c^2} \frac{\kappa_{es}}{\kappa_a}, \quad (2)$$

where κ_{es} and κ_a are the electron scattering and frequency-dependent absorption opacities, respectively. We can estimate the frequency-averaged y by using the frequency-averaged Rosseland opacity in Equation (2).

To examine the conditions under which Comptonization is important in this source, we may carry out a self-consistency check as follows. The emergent spectrum is well described as a modified blackbody (provided $\kappa_a \ll \kappa_{es}$), when $y \ll 1$. Using the characteristic temperature of the modified blackbody we can then estimate the range of parameters for which the effects of Comptonization may be neglected (and hence render the modified blackbody assumption valid). The Compton y parameter is given by

$$y \approx 1.3 \times 10^8 m^{-6} \alpha^2 \dot{m}^6 r^{-10} J_1^6, \quad (3)$$

in terms of the following dimensionless quantities: $r = R/r_g$, $m = M/(3M_\odot)$, $\dot{m} = \dot{M}/(10^{17} \text{gs}^{-1})$ and $J_1(R_i) \equiv 1 - (R_*/R_i)^{1/2}$. Thus, we see that y is less than one provided

$$r > 6.5 \alpha^{0.2} m^{0.6} \dot{m}^{0.6} J_1^{0.6}. \quad (4)$$

As we shall see below, especially as indicated by the solid curve in Figure 3, the important inner region of the disk does not satisfy this condition, and we must therefore take the effects of Comptonization into account.

When $y \gg 1$, the spectrum is effectively a Wien peak, whose temperature T_{wp} is approximately that of the disk at a depth z where the value of y to the surface is one:

$$y = \frac{4kT(z)}{mc^2} \tau_{es}^2(z) \approx 1. \quad (5)$$

Here, $\tau_{es}(z)$ is the scattering optical depth measured from the surface to a depth z , where the local disk temperature is $T(z)$. This approximation compares well with the results obtained using detailed radiative transfer equations (Ross, Fabian & Mineshige 1992). Now, the temperature variation along the vertical direction may be approximated as (e.g., Laor & Netzer 1989)

$$T(z) = T_{eff} \left(\frac{3}{4} \tau_{es}(z) \right)^{1/4}, \quad (6)$$

where T_{eff} is the effective temperature. Combining Equations (5) and (6) we therefore get

$$T_{wp} \approx T(z) \approx 9.8 T_{eff}^{8/9}. \quad (7)$$

In terms of the disk parameters this becomes

$$T_{wp} = 2.66 \times 10^7 \text{ K } m^{-0.44} \dot{m}^{0.22} r^{-0.66} J_1^{0.22}. \quad (8)$$

We note that the ratio $T_{wp}/T_{eff} \approx 1.7$ is nearly independent of these parameters, as has been pointed out by Shimura & Takahara (1995).

In their analysis of the data, Ebisawa et al. (1994) adopted a multicolor disk in order to infer the color temperature T_c . Since the spectrum from a multicolor disk closely resembles a Wien Peak this approximation yields a reasonable determination of the spectral temperature when we identify T_{wp} with the observationally inferred T_c . Thus, combining Equations (1) and (6), we get

$$r_i \approx 2.71 d m^{-1} J_2(r_i)^{-0.5} J_1(r_i)^{0.5} \mu^{-0.5} f^{0.5} T_*^{-2.27}, \quad (8)$$

and

$$\dot{m} \approx 0.46 d^3 m^{-1} J_2(r_i)^{-1.5} J_1(r_i)^{0.5} \mu^{-1.5} f^{1.5} T_*^{-2.27}, \quad (9)$$

where $f \equiv F_c/(2 \times 10^{-7} \text{ ergs cm}^{-2} \text{ s}^{-1})$, $d \equiv D/(1 \text{ kpc})$, $\dot{m} \equiv \dot{M}/(10^{17} \text{ g s}^{-1})$ and $T_* \equiv T_{wp}/(1 \text{ keV})$.

Using the tabulated values of the observed flux from the optically thick disk in Nova Musce and its observed color temperature as functions of time during the outburst (Ebisawa et al. 1994), we plot in Figure 1(a) the temporal evolution of r_i according to Equation (8). Only those data which correspond to the soft and ultra-soft states have been included since in the hard state the soft component is too weak to draw reliable inferences. In this figure, we have chosen the distance to the source to be 5 kpc, the mass of the black hole to be $3M_\odot$, $\mu = 0.5$ and $\alpha = 1$. It should be noted that although r_i and $\dot{m}$ individually depend sensitively on the parameters (m , d and μ), their interdependence does not.

We emphasize that the dependence of T_{wp}/T_{eff} on the disk parameters does not by itself bring out the variation in r_i . Without this dependence, i.e., assuming that the temperature ratio is constant, we would infer that $r_i \propto T_*^{-2}$ instead of $\propto T_*^{-2.27}$ as we have derived in Equation (8). A comparison of $r_i(t)$ for the case when T_{wp}/T_{eff} is constant

(Fig. 1(b); see also the plot in Ebisawa et al. 1994) with that provided in Figure 1(a) shows that the two are similar. Unlike earlier work, however, we shall here pay attention to the variation of r_i with time separately in the individual spectral states, as demarcated by the dashed lines in Figure 1(a): Region I is the ultra-soft state; II, the intermediate state between the ultra-soft and soft states; III, the soft state; and IV, the intermediate state between the soft and hard states.

In Figures 2 and 3 we show the variation of r_i as a function of the flux and $\dot{m}$, respectively. The solid line in Figure 3 is the radius versus $\dot{m}$ where the Compton y parameter equals one (see Eq. 4), assuming $\alpha = 1.0$. To the right of this curve, $y > 1$ and the effects of Comptonization must be taken into account, so that the use of Equations (8) and (9) is justified. When viewed state by state, there appears to be a significant correlation between r_i and $\dot{m}$.

Figure 4 shows the variation of $\dot{M}$ and the soft X-ray flux with time. We see that the accretion rate inferred with our analysis is in fact not proportional to the total flux, but rather is dependent on r_i and the soft flux.

A hard X-ray power-law was detected even when Nova Muscae was in the ultra-soft state. Since the disk is expected to be hot for $r \lesssim r_i$ (i.e., inside of the optically thick region), the presence of the hard X-ray component may be taken as an indirect confirmation that r_i is variable, since the inner edge would then presumably not extend down to the last stable orbit at $r \approx 3r_g$. Based on the result shown in Figure 4, however, we conclude that the inner hot region must then be advection dominated so that only a fraction of the dissipated gravitational energy is radiated away, in order not to exceed the observed high-energy flux. In Figure 5 we plot the ratio of the observed hard X-ray flux (1 – 20 keV) (taken from Ebisawa et al. 1993) to the rate of gravitational energy release in this inner region, versus $\dot{m}$. In this plot, we assume that the inner edge of the hot disk (i.e., R_*) lies at $3r_g$.

During the initial peak (i.e., the ultra soft state), this ratio is inversely proportional to the accretion rate—an expected result since the fraction of energy advected should increase

with $\dot{M}$ (Narayan & Yi 1995; Misra & Melia 1996b). The ratio continues to decrease as the accretion rate increases even in state II. Finally, in the next sequence of states, the ratio again increases with decreasing accretion rate as expected. Since there is a shift in this ratio between the two major states, it appears that the physical configuration of the hot disk is different during the ultra-soft (before 20 days) and soft states.

Figures 6, 7, 8 and 9 show the variation in τ_i with $\dot{m}$ for each of the spectral states individually. The solid lines represent the best fits to the data. For the ultra soft state (I), the straight line has a slope $s = .385^{+.20}_{-.19}$ ($\chi^2_{per\ d.o.f} = .02$), where the range corresponds to fits with a χ^2 at most double its minimum value. For the rest of the states we get: Intermediate state (II), $s = .83^{+.38}_{-.40}$ ($\chi^2_{per\ d.o.f} = .05$); Soft state (III), $s = .56^{+.31}_{-.33}$ ($\chi^2_{per\ d.o.f} = .74$); Intermediate state (IV), $s = .44^{+.09}_{-.10}$ ($\chi^2_{per\ d.o.f} = .003$).

3. Discussion

Several models have been proposed to describe a mechanism by which the inner region of an accretion disk could be converted from an optically thick to an optically thin state. In the standard model (Shapiro, Lightman & Eardley 1976), the transition occurs secularly when the radiation pressure dominates over gas pressure, due to local instabilities in the optically thick medium. The ratio of gas to radiation pressures using the expressions for $\dot{m}$ and τ_i we infer in this paper is

$$\frac{P_g}{P_r} \approx 0.29\ d^{-1.3}\ \dot{m}^{0.45}\ \alpha^{-0.1}\ J_2(\tau_i)^{0.67}\ J_1(\tau_i)^{0.12}\ \mu^{0.67}\ f^{-0.67}\ T_*^{-0.57}. \quad (10)$$

Interestingly, this ratio turns out to be of order unity as long as d is small (~ 1) and $\dot{m}$ is large. However, such a mechanism also predicts that $\tau_i \propto \dot{m}^{0.76}$ (obtained by setting $P_g/P_r = 1$), which does not appear to be consistent with the slopes found for states I and IV, where the χ^2 is small. It may be consistent with the behavior of states II (the intermediate state) and III (the soft state).

In an advection dominated disk model (Narayan & Yi 1995; Chen et al. 1995), the disk is expected to be in a hot, optically thin state whenever the accretion rate is less than some critical value. It is supposed that when $\dot{M}$ exceeds this value, the disk configures into

a cold optically thin state. This model predicts that τ_i should be inversely proportional to $\dot{m}$. But this too appears to be contrary to the results presented here.

In the transition disk model (Misra & Melia 1996a), the optically thick disk terminates when the effective optical depth is no longer much greater than one, hence rendering the optically thick disk solution inconsistent. For a radiation pressure dominated disk, τ_{eff} is proportional to $\dot{m}^{-2} r_i^{2.9}$. The radius at which $\tau_{eff} \rightarrow 1$ is therefore $\propto \dot{m}^{0.69}$. Although this trend is significantly better, this dependence is again not fully consistent with the slopes found in states I and IV.

We emphasize that the above discussion is for the soft and ultra-soft states, whereas the three theories described above were proposed to account for the high state. In addition, we have assumed in this paper that α is independent of $\dot{M}$, which may not be the case. However, since r_i and $\dot{m}$ depend only weakly on α this may not be serious. On the other hand if α is indeed strongly dependent on the disk parameters, this may account for the discrepancy between the observations and the above model(s). But at this stage, proposing such a dependence would be rather ad hoc.

A more careful analysis than that described here may finally make one of these models applicable not only to the high state, but also to the soft and ultra-soft states of Nova Muscae. For example, in the transition disk model the radiative cooling rate should be found self-consistently at the boundary where the optically thick disk terminates. In other words, it is not appropriate to use the optically thick disk solution to determine τ_{eff} as has been done thus far. The global disk solution should be obtained along the lines described in Misra & Melia (1996a). Such a model should also predict the high energy flux observed from this source. We defer this computation to a later date.

Similarly, it may be possible that the advection dominated disk theory is consistent with the results presented here, if the fraction of energy advected is obtained self-consistently within the transition phase. In analysis cited above, this fraction has been assumed to be independent of both the radius and the accretion rate. We note, however, that a global disk solution obtained with a similar model (Honma 1996) still predicts an inverse relation,

i.e., $\tau_i \propto \dot{m}^{-2}$.

In summary, the results presented here serve as a testing ground for models which predict transition from an optically thick to an optically thin disk. The hard X-rays probably arise from the innermost part of the accretion disk, though the manner in which the disk makes this transition is not yet fully understood. In addition, the disk structure appears to be different in the ultra-soft and soft states.

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Figure Captions

Figure 1 (a) Time evolution of the inner radius of the optically thick disk. The four different spectral states have been demarcated by the vertical dotted lines.

Figure 1 (b) Same as in Figure 1(a), except that the ratio of the color temperature to the effective temperature is here assumed to be independent of the disk parameters.

Figure 2. The evolution of the inner radius versus the soft energy flux.

Figure 3. The variation of inner radius with accretion rate. The solid line is the radius versus $\dot{m}$ when the Compton y parameter is set equal to one (Eq. 4, with $\alpha = 1.0$). Since all the data points are to the right of this line, Comptonization alters the emergent spectrum. The data pertaining to different spectral states are indicated by the different symbols, as shown.

Figure 4. The time evolution of the accretion rate (top panel) and soft X-ray flux (bottom panel).

Figure 5. The ratio of the observed high energy (hard X-ray) flux to the expected rate of gravitational energy release in the inner hot disk versus accretion rate. The rest of the energy implied by the decrease in this ratio with increasing $\dot{M}$ is presumably advected inwards through the event horizon.

Figure 6. The τ_i versus $\dot{m}$ relationship for the ultra-soft spectral state I. The solid line is the best fit to the data.

Figure 7. The τ_i versus $\dot{m}$ relationship for the intermediate spectral state II. The solid line is the best fit to the data.

Figure 8. The τ_i versus $\dot{m}$ relationship for the soft spectral state III. The solid line is the best fit to the data.

Figure 9. The τ_i versus $\dot{m}$ relationship for the intermediate spectral state IV. The solid line is the best fit to the data.

Figure 1 (b)

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9