Astron. Astrophys. 354, L67–L70 (2000)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

Black hole X-ray binaries: a new view on soft-hard spectral transitions

F. Meyer[1], **B.F. Liu**[1,2], **and E. Meyer-Hofmeister**[1]

[1] Max-Planck-Institut für Astrophysik, Karl Schwarzschildstrasse 1, 85740 Garching, Germany
[2] Yunnan Observatory, Academia Sinica. P.O.Box 110, Kunming 650011, P.R. China

Received 10 December 1999 / Accepted 21 January 2000

Abstract. The theory of coronal evaporation predicts the formation of an inner hole in the cool thin accretion disk for mass accretion rates below a certain value (≈ 1/50 of the Eddington mass accretion rate) and the sudden disappearance of this hole when the mass accretion rate rises above that value. The inner edge of the standard thin disk then suddenly shifts inward vvvvfrom about a few hundred Schwarzschild radii to the last stable orbit. This appears to quantitatively account for the observed transitions between hard and soft spectral states at critical luminosities. Due to the evaporation process the matter accreting in the geometrically thin disk changes to a hot coronal flow which proceeds towards the black hole as an advection-dominated accretion flow (ADAF; for a review see Narayan et al. 1998).

Key words: accretion, accretion disks – stars: binaries: close – black hole physics – X-rays: stars – stars: individual: A0620-00

1. Introduction

For a decade it has been known that the spectra of X-ray novae show changes from a soft state at high luminosity to a hard state when the luminosity has declined during the outburst (Tanaka 1989). The persistent canonical black hole system Cyg X-1 also undergoes occasional transitions between its standard low luminosity (hard) state and a soft state (see Fig. 1). Such changes between the two spectral states have been observed for several systems, regardless of whether the compact object is a neutron star (Aql X-1, 1608-522) or a black hole (GS/GRS 1124-684, GX 339-4) (Tanaka & Shibazaki 1996). Here we concentrate on black hole sources. Observations show that the phenomenon always occurs at a luminosity around $10^{37}\mathrm{erg/s}$, which corresponds to a mass accretion rate of about $10^{17}\mathrm{g/s}$ (Tanaka 1999).

The two spectral states are thought to be related to different states of accretion: (1) the soft spectrum originates from a thin disk which extends down to the last stable orbit plus a corona above the disk, (2) the hard spectrum originates from a thin disk outside a transition radius r_{tr} and a coronal flow/ ADAF inside. The spectral transitions of Nova Muscae 1991 and Cygnus X-1 were modelled based on this picture by Esin et al. (1997, 1998). The value of r_{tr} was taken as the maximal distance r for which an ADAF with that accretion rate can exist ("strong ADAF proposal", Narayan & Yi 1995). We determine the location of the inner edge of the thin disk from the equilibrium between it and the corona above.

Send offprint requests to: Emmi Meyer-Hofmeister

2. Generation of the coronal flow

2.1. Evaporation

The equilibrium between the cool accretion disk and the corona above (Meyer & Meyer-Hofmeister 1994) is established in the following way. Frictional heat released in the corona flows down into cooler and denser transition layers. There it is radiated away if the density is sufficiently high. If the density is too low, cool matter is heated up and evaporated into the corona until an equilibrium density is established (Meyer 1999).

Mass drained from the corona by an inward drift is replaced by mass evaporating from the thin disk as the system establishes a stationary state. When the evaporation rate exceeds the mass flow rate in the cool disk the disk terminates. Inside only a hot coronal flow exists.

2.2. Physics of the corona

Mass flow in the corona is similar to that in the thin disk. Differential (Kepler-like) rotation causes transfer of angular momentum outwards and mass flow inwards. The corona is geometrically much thicker than the disk underneath. Therefore sidewise energy transport is not negligible. Sidewise advection, heat conduction downward, radiation from the hot optically thin gas flow and wind loss are all important for the equilibrium between corona and thin disk. A detailed description would demand the solution of a set of partial differential equations in radial distance r and vertical height z. In particular a sonic transition requires treatment of a free boundary condition on an extended surface.

From simplified modelling and analysis we find the following pattern of coronal flow. When a hole in the thin disk exists there are three regimes with increasing distance from the black hole. (1) Near the inner edge of the thin disk the gas flows to-

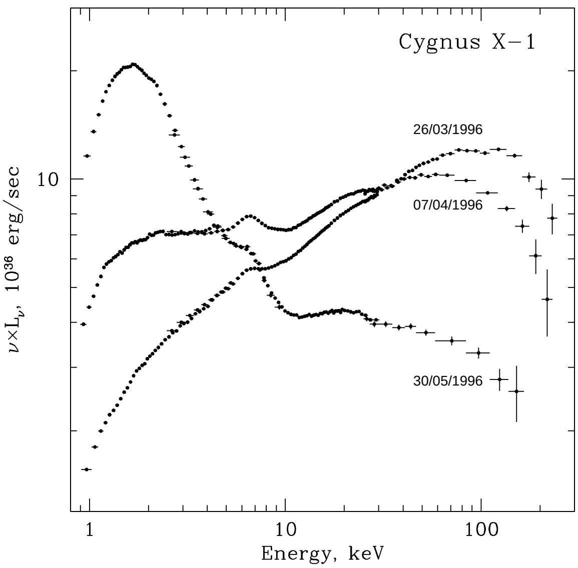

Fig. 1. Transition from the hard spectrum on 26/3/1996 to a soft spectrum on 30/5/1996, observed for Cygnus X-1 (from M. Gilfanov, E. Churazov, M.G. Revnivtsev, in preparation)

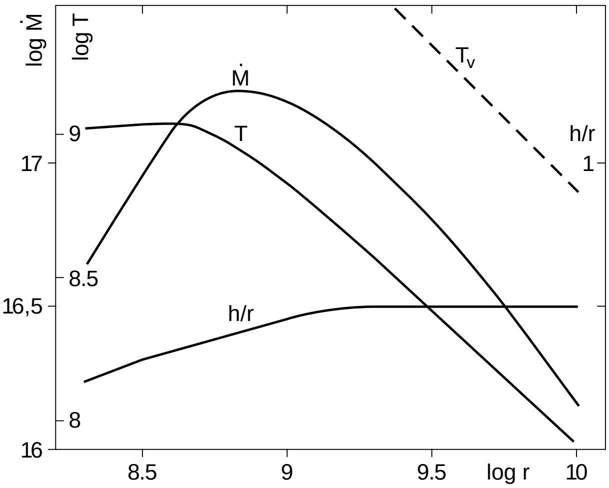

Fig. 2. Solid lines: rate of inward mass flow $\dot{M}$(in g/s) in the corona (= evaporation rate), maximum temperature in the corona and h/r (h pressure scaleheight) at the inner edge r=$r_{\rm tr}$ of the standard thin disk. Dashed line: virial temperature.

wards the black hole. (2) At larger r wind loss is important taking away about 20% of the total matter inflow. (3) At even larger distances some matter flows outward in the corona as a consequence of conservation of angular momentum. One might compare this with the flow in a "free" thin disk without the tidal forces acting in a binary. In such a disk matter flows inward in the inner region and outward in the outer region, with conservation of the total mass and angular momentum (Pringle 1981).

2.3. Model

We model the equilibrium between corona and thin disk in a simplified way. This is possible since the evaporation process is concentrated near the inner edge of the thin disk. Thus the corona above the innermost zone of the disk dominates the global structure. Further inward there is no thin disk anymore. The representative dominant region from r to r+Δr has to be chosen such that evaporation further outward is not important. One incorporates the effects of frictional heat generation, conduction, radiation, sidewise loss of energy and wind loss at large height into this one zone ("one-zone-model"). A set of ordinary differential equations for mass, motion, and energy with boundary conditions at the bottom (downward thermal flux - pressure relation) and at the top (sonic transition) *uniquely* determine mass accretion rate, wind loss and temperature in the corona as a function of radius. We restrict the analysis to a stationary corona.

The evaporation process was first investigated for disks in dwarf nova systems (Meyer & Meyer-Hofmeister 1994, Liu et al 1995). The situation is similar for disks around black holes (Meyer 1999). The coronal gas flowing into the hole and replaced by evaporation from the disk is understood as the supply for an ADAF which was used successfully to model the spectra of several black hole sources. A recent review by Narayan et al. (1998) gives a detailed description of accretion in the vicinity of a black hole.

3. Computational results

3.1. The critical mass flow rate $\dot{M}_{\rm crit}$

We use the same equations as Liu et al. (1995). The efficiency of evaporation at given distance r from the compact star determines the location of the inner edge of the thin disk $r_{\rm tr}$. The relation between the mass flow rate $\dot{M}$ in the disk and $r_{\rm tr}$ was now computed also for black hole systems. In Fig. 2 we show this relation for a 6 $M_\odot$ black hole (viscosity parameter α=0.3).

Up to now only the decreasing branch was known and investigated. The interesting new feature is that the efficiency of evaporation reaches a maximum. This means that as the mass accretion rate in the disk is increased the inner edge moves inward, but if the rate exceeds a critical value $\dot{M}_{\rm crit}$ the thin disk can no longer be fully depleted by evaporation (for this accretion rate the inner disk edge is at about 340 Schwarzschild radii). The thin disk then extends inward towards the last stable orbit.

The temperature in the corona increases with decreasing radius, but reaches a saturation value where the coronal mass flow reaches maximum. The value h in Fig. 2 is the height where the pressure has decreased by 1/e.

3.2. What causes the maximum of the coronal mass flow rate?

A change in the physical process that removes the heat released by friction is the cause for the maximum of the coronal mass flow rate seen in Fig. 2. A dimensional analysis of the equations yields the following result. For large inner radii coronal heating is balanced by inward advection and wind loss. This fixes the coronal temperature at about 1/8 of the virial temperature

T_v ($\Re T_v/\mu = GM/r$, $\Re$ gas constant, μ molecular weight, G gravitational constant) (see Fig. 2). Downward heat conduction and subsequent radiation in the denser lower region play a minor role for the energy loss though they always establish the equilibrium density in the corona above the disk.

With rising temperature, thermal heat conduction removes an increasing part of the energy released and finally becomes dominant. For optically thin bremsstrahlung the temperature saturates at a universal value defined by a combination of conductivity and radiation coefficients, the Boltzmann and the gas constant, and the non-dimensional α-parameter of friction, (see Fig. 2). Dimensional analysis of the equations yields the rate of mass accretion through the corona as a function of temperature divided by the Kepler frequency $(GM/r^3)^{1/2}$. For small radii this gives the $r^{3/2}$ law in Fig. 2.

The maximum accretion rate occurs where the sub-virial temperature for large radii reaches the saturation temperature for small radii. Since the virial temperature is proportional to M/r, this radius $r_{\rm crit}$ is proportional to M. Then the accretion rate, proportional to the inverse of the Kepler frequency, also becomes proportional to M.

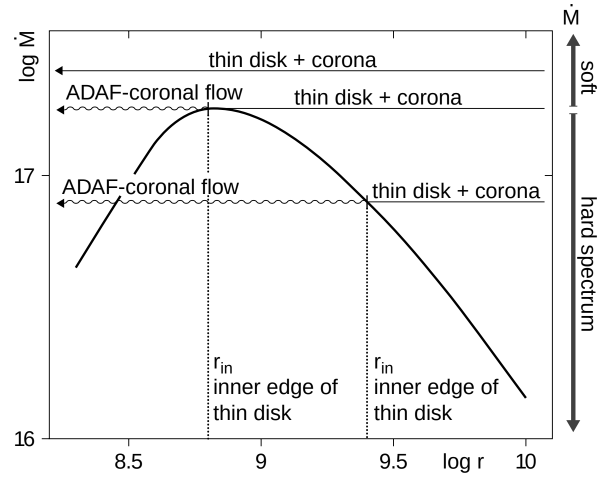

Fig. 3. Evaporation rate $\dot M(r)$ as in Fig. 2. Inward extension of the standard thin disk for 3 different mass flow rates $\dot M$ in the thin disk (schematic). Note that the standard thin disk reaches inward towards the black hole if $\dot M \geq \dot M_{\rm crit}$. Shown also the type of spectrum, soft or hard, related to $\dot M$.

3.3. Approximations used for our model

Synchrotron and Compton cooling have been left out. Synchrotron cooling is non-dominant as long as the magnetic energy density stays below roughly 1/3 of the pressure. Compton cooling and heating by photons from the disk surface and from the accretion centre are non-dominant at all distances larger than that of the peak of the coronal mass flow rate, $r \geq r_{\rm crit}$ ($\approx 340 R_s$, Fig. 2). They become important for smaller radii.

The conductive flux remains small compared to the upper limit, the transport by free streaming electrons, so that classical thermal heat conduction is a good approximation. We have neglected lateral heat inflow by thermal conduction. This term is small compared to the dominant advective and wind losses at large radii, and vanishes when the temperature becomes constant at small radii.

Temperature equilibrium between electrons and ions requires that the collision times between them remains shorter than the heating timescale. This holds for $r \geq r_{\rm crit}$, but the condition fails for $r < r_{\rm crit}$ where a two temperature corona can develop.

Tangled coronal magnetic fields could reduce electron thermal conductivity. We note however that reconnection and evaporation tend to establish a rather direct magnetic path between disk and corona.

4. Spectral transitions

4.1. Predictions from the evaporation model

At maximum luminosity of an X-ray nova outburst the mass accretion rate is high and the thin disk extends inward to the last stable orbit. A corona exists above the thin disk, but the mass flow in the thin disk is so high that no hole appears. In decline from outburst the mass accretion rate decreases. When $\dot M_{\rm crit}$ is reached a hole forms at $\approx$ 340 R_s and the transition soft/hard occurs. If the mass accretion rate varies up and down as in high-mass X-ray binaries we expect hard/soft and soft/hard transitions. In Fig. 3 we show the expected behaviour schematically.

The descending branch for smaller r indicates the possibility that an interior disk could form. We note that a gap exists between the exterior standard thin disk and an interior disk. In this gap the flow assumes the character of an ADAF with different temperature of ions and electrons, due to its high temperature and poor collisional coupling. This provides the possibility that the interior disk fed by this flow has a two temperature corona on top, different from a standard thin disk plus corona in the high state. We will discuss this in a further investigation.

4.2. Comparison with observations

The three persistent (high-mass) black hole X-ray sources LMC X-1, LMC X-3 and Cyg X-1 show a different behaviour. LMC X-1 is always in the soft state (Schmidtke et al. 1999). For LMC X-3, most of the time in the soft state, recently recurrent hard states have been detected (Wilms et al. 1999). Cyg X-1 spends most of its time in the hard state with occasional transitions to the soft state (see e.g. Fig. 1). This can be interpreted as caused by different long-term mean mass transfer rates: the highest rate (scaled to Eddington luminosity) in LMC X-1, the lowest in Cyg X-1, and in between in LMC X-3. Transient sources show a soft/hard transition during the decay from outburst. The best studied source is the X-ray Nova Muscae 1991 (Cui et al. 1997).

The transition always occurs around $L_X \approx 10^{37}$ erg/s (Tanaka 1999). Our value for the critical mass accretion rate for a 6 $M_\odot$ black hole, $10^{17.2}$g/s, corresponds to a standard accretion disk luminosity of about $10^{37.2}$ erg/s. This is very close agreement.

For accretion rates below $\dot{M}_{\rm crit}$ the location of the inner edge of the standard thin disk derived from the evaporation model also agrees with observations (Liu et al. 1999).

At the moment of spectral transition our model predicts the inner edge near 340 Schwarzschild radii. The observed timescale for the spectral transition of a few days (Zhang et al. 1997) agrees with the time one obtains for the formation of a disk at 340 R_s with an accretion rate $\dot{M}_{\rm crit}$.

But even in the low state X-ray observations of a reflecting component indicates the existence of a disk further inward, at 10 to 25 R_s (Gilfanov et al. (1998), Zycki et al. (1999)). This might point to a non-standard interior disk as discussed above and explain why the spectral transitions in Cygnus X-1 could be well fitted by Esin et al. (1998) with a disk reaching inward to $\leq 100R_s$.

5. Conclusions

We understand the spectral transition as related to a critical mass accretion rate. For rates $\dot{M} \geq \dot{M}_{\rm crit}$ (the peak coronal mass flow rate) the standard disk reaches inward to the last stable orbit and the spectrum is soft. Otherwise the ADAF in the inner accretion region provides a hard spectrum. At $\dot{M}_{\rm crit}$ the transition between dominant advective losses further out and dominant radiative losses further in occurs. Except for the difference between the sub-virial temperature of the corona and the closer-to-virial temperature of an ADAF of the same mass flow rate, this same critical radius is predicted by the "strong ADAF proposal" (Narayan & Yi (1995). In general however, the strong ADAF proposal results in an ADAF region larger than that which the evaporation model yields.

The transition between the two spectral states has been observed for black hole and neutron star systems, in persistent and transient sources (Tanaka & Shibazaki 1996, Campana et al.1998). This points to similar physical accretion processes. Menou et al. (1999) already discussed the accretion via an ADAF in neutron star transient sources. Our results should also be applicable.

The relations for a 6 $M_\odot$ black hole plotted in Fig. 2 can be scaled to other masses: in units of Schwarzschild radii and Eddington accretion rates the plot is universal. The application to disks around supermassive black holes implies interesting conclusions for AGN.

Acknowledgements. We thank Marat Gilfanov, Eugene Churazov and Michael Revnivtsev for the spectral data of Cygnus X-1.

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