BLACK HOLE X-RAY BINARIES: THE TRANSITION FROM THE COOL THIN DISK TO THE CORONAL FLOW

Friedrich Meyer (1), Bifang Liu (1,2) and Emmi Meyer-Hofmeister (1)
(1)Max-Planck-Institut für Astrophysik, Karl Schwarzschildstr. 1,
D-85740 Garching, Germany
(1,2) and Yunnan Observatory, Chinese Academy of Sciences, P.O.Box 110, Kunming 650011, China

Abstract Coronal evaporation in the inner parts of accretion disks around black holes provides the matter flow for ADAFs (advection dominated accretion flows). This physical process predicts the formation of an inner hole in the cool thin accretion disk for mass accretion rates below a certain threshold and the sudden disappearance of this hole when the mass accretion rate rises above that threshold. This appears to quantitatively account for the observed transitions between hard and soft spectral states at critical luminosities.

1. INTRODUCTION

Recently a wealth of X-ray observations has provided more detailed information about spectra of X-ray sources and short-time variability. This concerns soft X-ray transients as good examples of stellar accreting black holes, high-mass X-ray binaries with a black hole primary star, and also Active Galactic Nuclei. The new observations put more stringent constraints on the modelling of accretion processes. In this connection the change from accretion in a standard cool disk to a hot coronal flow is an important feature.

Different solutions of accretion onto compact objects had been investigated in the past. An account can be found in the recent review by Narayan et al. (1998). The description of an optically thin, geometrically thick disk, now often called "standard thin disk", goes back to work of Shakura & Sunyaev (1973), Novikov & Thorne (1973), Lynden-Bell & Pringle (1974) and others. A much hotter self-consistent solution of optically thin gas was discovered by

Shapiro, Lightman and Eardley (1976), but found to be thermally unstable by Piran (1978). A solution for even super-Eddington accretion rates in which the large optical depth of the inflowing gas prevents radiation was suggested by Katz (1777), Begelman (1978), Abramowicz et al. (1988) and others. This is an optically thick advection-dominated accretion flow. The fourth solution concerns accretion at low sub-Eddington rate (proposed by Shapiro (1976), Ichimaru(1977) and Rees et al. 1982) Detailed theoretical work on this solution by several authors has proven that this optically thin regime of solutions for low accretion rates is relevant for accretion in many cases (Narayan and Yi (1994, 1995a 1995b), Abramowicz et al. 1995, Chen 1995; Chen et al. 1995, 1997; Narayan, Kato et Homna 1997.

The model of an optically thin advection-dominated flow (ADAF) allows to explain the accretion in soft X-ray transients during quiescence. Assuming the old picture of an standard thin accretion disk reaching inward towards the black hole the amount of X-ray flux is clearly inconsistent with the accretion rate estimated from the outer optically thick disk (McClintock et al. 1995). The nature of the ADAF allows to understand the accretion as changing from a standard thin disk to the hot flow at a certain transition radius. The black hole X-ray transients are a laboratory of accretion onto black holes. The physics of the accretion processes around supermassive black holes in AGN is similar, which makes the investigation of ADAF even more important and fruitful.

The change from a geometrically thin disk to the hot flow is an essential feature in this overall picture of accretion. The "strong ADAF principle", worked out by Narayan and Yi (1995), suggests that, for a given accretion rate, an ADAF exists whereever the energy produced by friction cannot be radiated away by a thin disk. This rule provides a transition radius $r_{\rm tr}$ for a given accretion rate (see Fig. 6b in Esin et al. 1997). The aim of our work is to find the transition radius between thin disk and a coronal flow from the equilibrium of the cool disk and the corona above. The co-existence of a cool disk and a corona had been investigated for disks in dwarf nova systems, where features otherwise not understood as for example the X-rays observed in quiescence can then be explained (Meyer & Meyer-Hofmeister 1994, Liu et al. 1995). The situation is the same in disks around black holes (Meyer 1999), both stellar and supermassive. In the present contribution we describe the physics of the coronal flow and the interaction with the cool disk underneath.

In the following we discuss the general features of evaporation, describe the results from our computations, especially the recently found critical mass flow rate. We point out the invariance of our results for different black hole masses and the applicability to supermassive black holes.

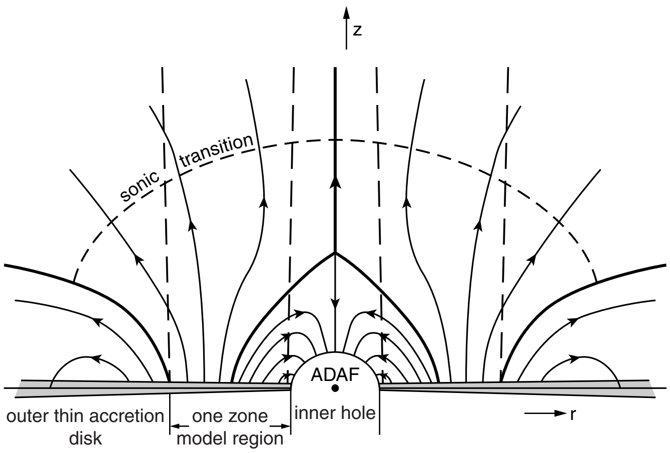

Figure 1.1 Coronal mass flow pattern (schematic)

2. GENERAL FEATURES OF EVAPORATION

The equilibrium between the cool accretion disk and the corona above 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. Mass drained from the corona by an inward drift is steadily replaced by mass evaporating from the thin disk as the system reaches a stationary state. This evaporation rate increases steeply with decreasing distance from the central compact star. When the evaporation rate exceeds the mass flow rate in the cool disk, a hole forms up to the distance where both rates are equal. Inside this transition radius $r_{\rm tr}$ only a hot coronal flow exists.

The mass flow in the corona is similar to that in the thin disk. The matter has still its angular momentum, and differential (Kepler-like) rotation causes friction. The main part of the coronal gas flows towards the center directly. For conservation of angular momentum a small part flows outward in the coronal layer and condensates in the outer cool disk. Since the temperature is very high the corona is geometrically much thicker than the disk underneath. Therefore processes as sidewise energy transport, advection and heat conduction downward are important for the equilibrium between corona and thin disk, together with radiation from the hot optically thin gas and wind loss. The physical two-dimensional situation demands 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.

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 and we can choose a region from r to $r+\Delta r$ which is representative such that the main interaction between cool disk and corona occurs there and evaporation further outward is not important. In Fig. 1 we show the flow pattern as derived from analysis and simplified modelling for the case that a hole in the thin disk exists There are three regimes. (1) Near the inner edge of the thin disk the gas flows towards 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)).

3. COMPUTATIONAL RESULTS

3.1 CORONAL STRUCTURE

We took $6M_\odot$ as our standard parameter value to model the evaporation in accretion disks around stellar black holes (for a detailed description see Meyer, Liu and Meyer-Hofmeister 2000). We compute the structure of the corona for distances from the black hole ranging from large values corresponding to an outer cool disk to small values. For different distances r the structure in z direction is similar if plotted in z/r. In Fig. 2 we show the structure at $r = 10^{8.8}$cm. Within a narrow range in z pressure and density decrease. The downward conductive heat flux therefore also has its maximum a low height z and approaches zero at higher z and is negliglbly small when sound transition $v_z/V_{\rm s}$=1 is reached. The temperature is practically constant in the layers higher up in the corona.

We use the same equations as Liu et al. (1995). We computed the coronal structure for different black hole masses and accretion rates. As can be seen from the dertermining equations the coronal structure scales with the Schwarzschild radius $r_{\rm s}$=$2GM/c^2 = 2.95 \times 10^5 M/M_\odot$ cm and accretion rate in Eddington units, $M_{\rm Edd}$=$L_{\rm Edd}/\eta c^2$=$1.39 \times 10^{18} M/M_\odot$ gs^{-1} (η=0.1). This is an important feature of evaporation. The situation is the same for cataclysmic variables, where the compact star is a white dwarf, for neutron stars (which we do not discuss here), for stellar and also for supermassive black holes. The applicability to disks around supermassive black holes allows further insight to AGN.

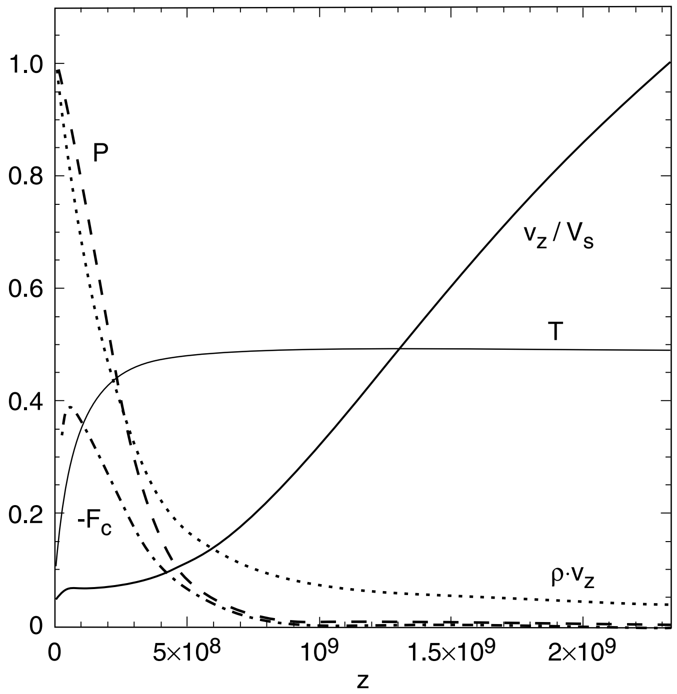

Figure 1.2 Coronal structure at distance $r = 10^{8.8}$cm from the $6M_\odot$ black hole. Temperature T is given in units of 0.2× virial temperature, pressure P and vertical mass flow $\rho \times v_z$ (v_z vertical velocity) are scaled to their value at the lower boundary. -F_c is the downward conductive heat flux, measured in the frictional energy generation rate in a column of unit cross section. V_s is the sound velocity.

3.2 THE CRITICAL MASS FLOW RATE

The efficiency of evaporation at given distance r from the compact star determines the location of the inner edge of the thin disk r_{tr}. The relation between the mass flow rate $\dot{M}$ in the disk and r_{tr} was now computed also for black hole systems. In Fig. 3 we show this relation for a 6 $M_\odot$ black hole (viscosity parameter α=0.3).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. 3 is the height where the pressure has decreased by 1/e. Up to now only the decreasing branch was known and investigated. The interesting new feature is that the efficiency of evaporation reaches a maximum. We describe the consequences in the following. The existence of a maximum 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.

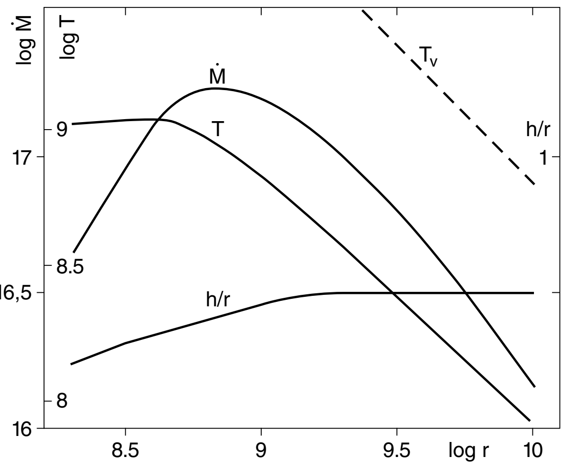

Figure 1.3 Solid lines: rate of inward mass flow $\dot{M}$(in g/s) in the corona (= evaporation rate), maximum temperature in the corona and h/r (h pressure scaleheight) at the inner edge r=$r_{\rm tr}$ of the standard thin disk. Dashed line: virial temperature.

3.3 TRANSITIONS OF THE SPECTRUM

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. 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 $10^{37}\rm erg/s$, which corresponds to a mass accretion rate of about $10^{17}\rm g/s$ (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 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). In the evaporation model the computed evaporation effeiciency determines the location of the inner edge of the thin disk from the equilibrium between it and the corona above.

3.4 THE CAUSE OF 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. 3. 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 $T_{\rm v}$ ($\Re T_{\rm v}/\mu = GM/r$, $\Re$ gas constant, μ molecular weight, G gravitational constant) (see Fig. 3). 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. 3). 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. 3.

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.

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.

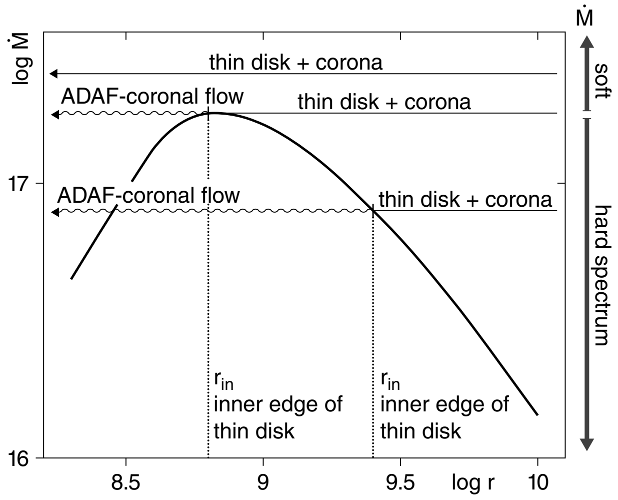

Figure 1.4 Evaporation rate $\dot{M}(r)$ as in Fig. 2. Inward extension of the standard thin disk for 3 different mass flow rates $\dot{M}$ in the thin disk (schematic). Note that the standard thin disk reaches inward towards the black hole if $\dot{M} \geq \dot{M}_{\rm crit}$. Shown also the type of spectrum, soft or hard, related to $\dot{M}$

.

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 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 indicate 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.

References

Abramowicz M.A., Czerny B., Lasota J.P. et al., 1988, ApJ 332, 646

Abramowicz M.A., Chen X., Kato S. et al., 1995, ApJ Letters 438, L37
Begelman M.C., 1978, MNRAS 243, 610
Campana S., Colpi M., Mereghetti S., 1998, A&A Rev. 8, 269
Chen X., 1995, MNRAS 275, 641
Chen X., Abramowicz M.A., Lasota J.P., Narayan R., Yi I., 1995, ApJ 443, L61
Chen X., Abramowicz M.A., Lasota J.P., 1997, ApJ Letters 476, L61
Cui W., Zhang S.N., Focke W. et al., 1997, ApJ 484,383
Esin A.A., McClintock J.E, Narayan R., 1997, ApJ 489, 865
Esin A.A., Narayan R., Cui W. et al., 1998, ApJ 505, 854
Gilfanov M.R.,0 Churazov E.M., Revnivtsev M., 2000, in preparation
Ichimaru S., 1977, ApJ 214, 840
Katz J., 1977, ApJ 215, 265
Liu F.K., Meyer F., Meyer-Hofmeister E., 1995, A&A 300, 823
Liu B.F., Meyer F., Meyer-Hofmeister E., 1997, A&A 328, 247
Liu B.F., Yuan W., Meyer F., Meyer-Hofmeister E., Xie G., 1999, ApJ 527
Lynden-Bell D., Pringle J.E., 1974, MNRAS 168, 603
McClintock J.E., Horne K., Remillard R.A., 1995, ApJ 442 358
Menou K., Esin A., Narayan R. et al., 1999, ApJ 520, 276
Meyer F., 1999, in: Proc. of Disk Instablities in Close Binary Systems, eds. S. Mineshige and J.C. Wheeler, Universal Academic Press, Kyoto, p.209
Meyer F., Meyer-Hofmeister E. 1994, A&A 288, 175
Meyer-Hofmeister E., Meyer, 1999, A&A 348,154
Meyer-Hofmeister E., Meyer F., Liu B.F., 1998, A&A 339, 507
Mineshige S., Liu B.F., Meyer F., Meyer-Hofmeister E. 1998, PASJ 50, L5
Narayan R., McClintock J.E., Yi I. 1996, ApJ 457, 82
Narayan R., Barret D., McClintock J.E., 1997, 482, 448
Narayan R., Mahadevan R., Quartaert E., 1998, in: The Theory of lack Hole Accretion Discs, eds. M.A. Abramowicz et al., Cambridge University Press, p.148
Narayan R., Yi, 1994, ApJ Letters 428, L13
Narayan R., Yi, 1995a, ApJ 444, 231
Narayan R., Yi, 1995b, ApJ 452, 710
Narayan R., Kato S., Homna F., 1997, ApJ 476, 49
Novikov I.D., Thorne K.S., 1973 in: Black Holes, eds. C. DeWitt and B. DeWitt, Gordon & Breach, p.343
Piran T., 1978, ApJ 221, 652
Pringle J.,1981, Ann. Rev. Astron. Astrophys. 137
Rees M.J., Begelman M.C., Blandford R.D. et al., 1982, Nature 295, 17
Schmidtke P.C., Ponder A.L., Cowley A.P., 1999, Astron.J., 117, 1292
Shakura N.I., Sunyaev R.A., 1973, A&A 24, 337 ,1995, ApJ 446,741

Shapiro S.L., Lightman A.P., Eardly D.M., 1976, ApJ 204, 187 bibitemref:84 Tanaka Y.,1989, in: Proc. 23rd ESLAB Symp. Two-Topics X-Ray Astronomy, Bologna ESA SP-296, p.3

Tanaka Y.,1999, in: Proc. of Disk Instablities in Close Binary Systems, eds. S. Mineshige and J.C. Wheeler, Universal Academic Press, Kyoto, p.21

Tanaka Y., Shibazaki N., 1996, ARA&A, 34, 607

Wilms J., Nowak M.A., Pottschmidt K., et al. 1999, astro-ph 9910508

Zhang S.N., Cui W., Harmon B.A. et al., 1997, ApJ 477, L95

Zycki T., Done C., Smith D.A., 1999, MNRAS 305, 23