Astron. Astrophys. 348, 154–160 (1999)

ASTRONOMY AND ASTROPHYSICS

Black hole soft X-ray transients: evolution of the cool disk and mass supply for the ADAF

E. Meyer-Hofmeister and F. Meyer

Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Strasse 1, D-85740 Garching, Germany

Received 16 March 1999 / Accepted 17 May 1999

Abstract. Using the black hole transient X-ray source A0620-00 as an example we study the physical interplay of three theoretical constituents for modelling these transient sources: (1) the advection-dominated accretion flow (ADAF) onto the central black hole, (2) the evaporation of matter from the cool outer disk forming a coronal flow and (3) standard disk evolution leading to outburst cycles by accretion disk instability (dwarf nova mechanism).

We investigate the evolution of accretion disks during quiescence including the evaporation of gas in the inner part of the disk. About 20% of the matter is lost in a wind from the corona. The mass flow rate obtained from our model for the coronal flow towards the black hole, is about half of the matter flowing over from the companion star. It agrees with the rate independently derived from the ADAF spectral fits by Narayan et al. (1997). About one third of the matter accumulates in the outer cool disk. The computed disk evolution is consistent with the observational data from the outburst in 1975. The evolution of the accretion disk until the instability is reached shows that the critical surface density can not be reached for rates only slightly less than the rate derived here for A0620-00. Systems with such accretion rates would be globally stable, suggesting that many such faint permanently quiescent black hole X-ray binaries exist.

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

1. Introduction

Soft X-ray transients (SXT) are binaries in which a black hole or a neutron star primary accretes matter from a main sequence or giant secondary (van Paradijs & McClintock 1995, Tanaka & Shibazaki 1996). Several sources containing a black hole show outbursts every few decades, which last a few months. During the long-lasting quiescent state the systems are very dim (McClintock & Remillard 1990, McClintock et al. 1995). The X-ray luminosity observed during this state from binaries containing a black hole is systematically lower than that from systems with a neutron star. But the luminosity from the neutron star systems is not as high as expected for accretion of all matter at the neutron star's surface. For a recent compilation of ASCA observations of SXTs in quiescence see Asai et al. (1998). It was suggested that in the neutron star systems part of the matter is thrown out by a magnetic propeller (Illarionov & Sunyaev 1975) and therefore the luminosity is reduced (Asai et al. 1998, Menou et al. 1999b).

For the X-ray nova A0620-00 in quiescence the comparison of observed optical and X-ray luminosity showed that the observed X-ray flux is much less than expected if one assumes the same accretion flow everywhere in the disk (see McClintock et al. 1995 and references therein). This observation led to the suggestion that most of the thermal and kinetic energy is carried into the black hole by an advection-dominated accretion flow (ADAF) and is not radiated away. The ADAF model includes the physics of the hot accretion flow (Narayan et al. 1996, 1997, for a recent review see Narayan et al. 1999) and is successful in describing the observed spectra of black hole SXTs in quiescence. It provides strong evidence for the black hole nature of the accreting primaries.

The configuration of the black hole SXT is the following. Matter from the Roche-lobe filling secondary star flows over to an accretion disk. In quiescence the disk is cool in the outer part. At a certain transition radius, more accurately a transition region, the accretion flow is transformed into a hot coronal flow and farther in no underlying cool disk exists anymore (Esin et al. 1997). This coronal flow continues inward and, at very high temperatures, becomes an advection-dominated accretion flow. For a schematic drawing see Fig. 1.

Our present investigation studies evaporation as the source of the matter for the ADAF. We have shown earlier (Meyer & Meyer-Hofmeister 1994, Liu et al. 1995, Liu et al. 1997) that evaporation of matter from a cool disk into an overlying hot corona is important for the evolution of accretion disks in binaries during quiescence. The same process works in dwarf nova disks and in disks of X-ray novae (Mineshige et al. 1998). In dwarf nova disks the inner part of the disk around the white dwarf primary can be evaporated, depending on the amount of mass flow in the cool disk. In black hole SXTs the horizon lies at much smaller radii and the coronal flow continues into a probably more spherical inner area filled with very hot gas.

Send offprint requests to: emm@mpa-garching.mpg.de

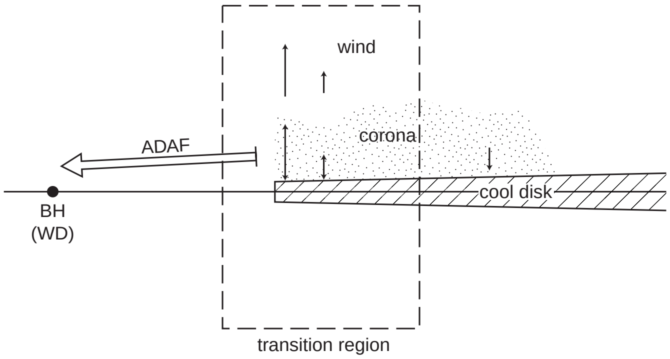

Fig. 1. Schematic drawing of cool disk, corona and ADAF

If the standard thin accretion disk would extend to such small radii with the same mass flow rate as in the outer regions the matter would become ionized and the disk instability would not allow the whole disk to remain in a quiescent state. Lasota et al. (1996) pointed out that the inner part of the thin disk has to be truncated.

In Sect. 2 we discuss the physics of the evaporation process applied to a black hole source. We point out that the interaction of evaporation and mass accretion in the cool disk are similar for dwarf novae and transients. We compute the disk evolution using the well observed system A0620-00 as an example (Sect. 3). In Sect. 4 we compare our results with the findings from the spectral fit based on the ADAF model. In Sect. 5 we summarize the general features.

2. Evaporation in disks around white dwarfs and black holes

2.1. The evaporation process in disks around black holes

We analyse the disks around black holes. The situation for disks around neutron stars is more complex. Irradiation by the hot neutron star surface has to be taken into account. But it is expected that for both, black hole and neutron star sources the accretion flow near the compact star occurs as an ADAF (Menou et al. 1999b).

The evaporation model decribes how above the cool inert disk a hot self-sustained coronal layer is built up, fed by matter from the disk underneath (Meyer & Meyer-Hofmeister 1994, Meyer 1999). The vertical structure of the corona is established by the balance between heat generation and radiation losses at the coronal-chromospheric transition layer. Based on a one-zone model Liu et al. (1995) computed the evaporation rate $\dot{M}_{\rm ev}$ (evaporation into the corona above and below the cool disk, both sides) for different white dwarf masses up to $1.2\,M_\odot$. The rate varies with the distance to the primary star r and its mass M_1 as

$$\dot{M}_{\rm ev} = 10^{15.6} \left(\frac{r}{10^9 {\rm cm}}\right)^{-1.17} \left(\frac{M_1}{M_\odot}\right)^{2.34} \quad [{\rm gs}^{-1}]. \qquad (1)$$

Due to wind loss the coronal mass flow rate at the inner edge of the cool disk towards the compact object, $\dot{M}_{\rm acc}$, is about 80% of $\dot{M}_{\rm ev}$.

We checked the applicability of this result to larger compact object masses with respect to the following physical conditions: the electron-proton collision frequency is high enough that equilibrium is established within the dynamical timescale, the mean free path of transporting electrons is small compared to the temperature scale length in the conductive boundary layer. The ratio of advective to conductive energy flux remains the same. All these three ratios remain nearly invariant for large changes in central mass.

2.2. The balance between mass accretion and evaporation

An important feature of the accretion disk in quiescence is the existence of a transition between cool disk and hot coronal flow. To evaluate the transition radius $r_{\rm trans}$ one needs to know the mass flow rate $\dot{M}_{\rm d}$ in the disk. The assumption of a quasi-stationary disk allows such an estimate. To determine how this location changes during the long period of quiescence one has to compute the evolution of the disk. We describe here briefly earlier results to show the similarity in the evolution of the inner disk in different binaries. To follow such a disk evolution it is necessary to include conservation of mass and angular momentum in the interacting cool disk and corona (Liu et al. 1997). The angular momentum released farther inside by the accreting matter flows outward in the corona and even forces a small part of coronal matter to flow outward. This matter condenses later in the outer cool disk (compare Fig. 4).

2.2.1. Ordinary dwarf nova

Liu et al. (1997) studied the evolution of the disk around a $1\,M_\odot$ primary star in an ordinary dwarf nova system with a relatively high mass overflow rate of $\dot{M}$= $2\,10^{-9} M_\odot/{\rm yr}$ from the secondary. Disk evaporation creates a hole in the inner disk and the transition remains near $r = 4\,10^9$ cm while matter piles up in the outer disk until the onset of instability occurs near $r = 10^{10}$ cm. Without evaporation this would have happened near to the white dwarf surface. For a comparison of accretion disk instabilities in dwarf novae and transient X-ray sources see Cannizzo (1998).

2.2.2. WZ Sge stars

WZ Sge stars, a subgroup of dwarf nova (Ritter & Kolb 1998), have also very long outburst recurrence times similar to black hole SXTs considered here (Kuulkers 1999). This makes WZ Sge an interesting candidate to study the effect of evaporation. For the parameters we had chosen according to observations (Meyer-Hofmeister et al. 1998) we found that during the first years of quiescence the mass flow rate in the inner disk is lower than the evaporation rate, $\dot{M}_{\rm d} \le \dot{M}_{\rm ev}$, and a hole is formed. With the increasing accumulation of matter $\dot{M}_{\rm d}$ rises and the transition shifts towards the white dwarf until after about 9 years the hole is closed. Evaporation goes on all the time, even after the inner edge of the disk has reached the white dwarf surface,

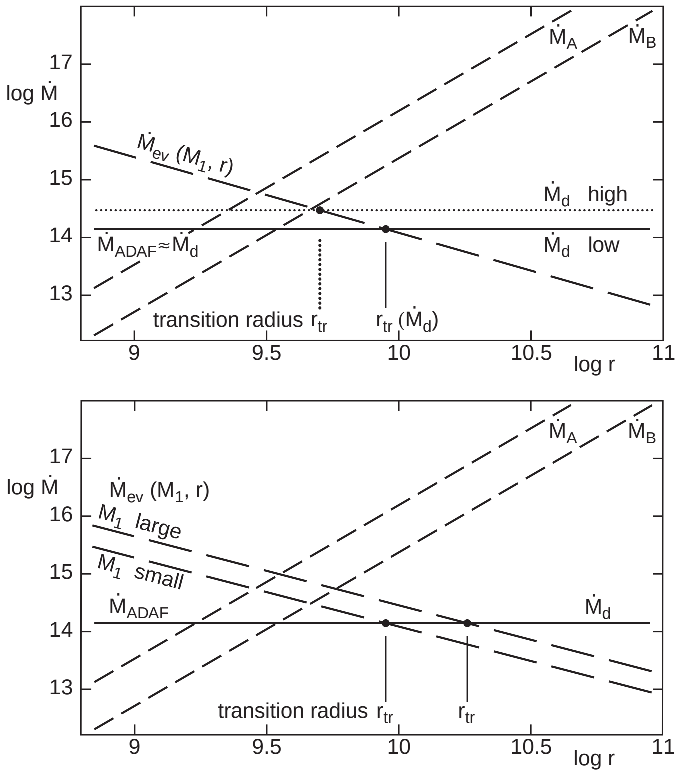

Fig. 2. Schematic drawing for the adjustment of the transition radius $r_{\rm tr}$ (=location of the transition between cool disk and coronal flow). $r_{\rm tr}$ depends on the evaporation rate $\dot{M}_{\rm ev}$ and on the mass flow rate $\dot{M}_{\rm d}$ in the cool disk, M_1 primary mass. The upper panel shows $\dot{M}_{\rm ev}$ [Eq. 1] and $r_{\rm tr}$ for 2 different rates $\dot{M}_{\rm d}$: for lower $\dot{M}_{\rm d}$ the transition occurs farther out. For explanation of the critical mass flow rates $\dot{M}_{\rm A}$ and $\dot{M}_{\rm B}$ see Fig. 3 where the corresponding values $\Sigma_{\rm A}$ and $\Sigma_{\rm B}$ are given. The lower panel shows $\dot{M}_{\rm ev}$ for 2 different primary masses and the resulting change of $r_{\rm tr}$: for smaller M_1 the transition occurs farther in. (cgs units)

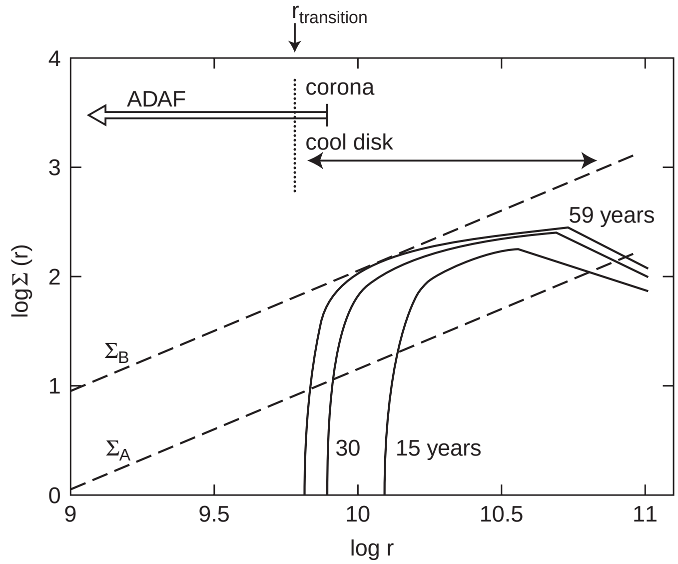

Fig. 3. Disk evolution of A0620, "standard case", accumulation of matter in quiescence. $\Sigma_{\rm A}$ and $\Sigma_{\rm B}$ critical surface densities. For the surface densities between these values two states, hot and cold, are possible. When accumulation of matter reaches $\Sigma_{\rm B}$ an outburst sets in until the outburst is triggered (Fig. 1, Meyer-Hofmeister et al. 1998).

2.2.3. General aspects

Generally the inner edge of the cool disk will be established where the evaporation rate equals the mass flow rate in the disk. This balance determines the transition radius if the mass of the primary and the mass flow rate in the disk are known. The fact that the disks are quasi-stationary during long quiescence intervals allows a first estimate for $r_{\rm trans}$. We show in a schematic drawing how $r_{\rm trans}$ changes if $\dot{M}_{\rm d}$ changes (Fig. 2a) and how a different primary mass influences the evaporation rate $\dot{M}_{\rm ev}$ and therefore the location of the transition.

3. The evolution of the accretion disk in the black hole soft X-ray transient A0620-00 during quiescence

The system A0620-00 (Nova Mon 1917, 1975), discovered by *Ariel* in 1975 (Elvis et al. 1975), is one of the best studied X-ray novae. For a recent detailed compilation of the observations for A0620-00 see Kuulkers (1998). The very first theoretical investigations of the accretion disk (Huang & Wheeler 1989 and Mineshige & Wheeler 1989) aimed to clarify whether the outburst behaviour of A0620-00 could be understood as an accretion disk instability. In later work the emphasis was put mostly on modelling the observed exponential decay of the outburst luminosity. Recently Cannizzo (1998) reviewed these investigations and included an example of outburst modelling based on disk evolution with an assumed law for loss of matter from the cool inner disk, but without the flow of angular momentum in the combined disk + coronal accretion.

Our investigation concentrates on the evolution of the accretion disk during quiescence using a computer code which includes the physics of interaction of disk and corona (see Sect. 3.1). Observations for this state are more difficult, but have been carried out in the optical, UV, EUV and X-ray bands. For a description of the observations and deduction of system parameters see Narayan et al. (1996, 1997). The orbital period is 7.8 hr (McClintock et al. 1983). The mass of the black hole follows from the mass function if the inclination is known. Narayan at al. (1996,1997) considered different values for the inclination i and the corresponding primary mass M_1: i=70° and M_1=$4.4\,M_\odot$, i=40° and M_1=$12\,M_\odot$ and in the later paper also i=55° and M_1=$6.1\,M_\odot$, as recently suggested by Barret et al. (1996).

3.1. Technique of computations

For our modelling of the disk evolution we take BH masses of $4\,M_\odot$ and $6\,M_\odot$. The viscosity parameter (Shakura & Sunyaev 1973) assumed was $\alpha_{\rm cool}$= 0.05, a standard value for the cool disk in dwarf nova outburst modelling. We assume that only a small amount of matter was left over in the disk after the last

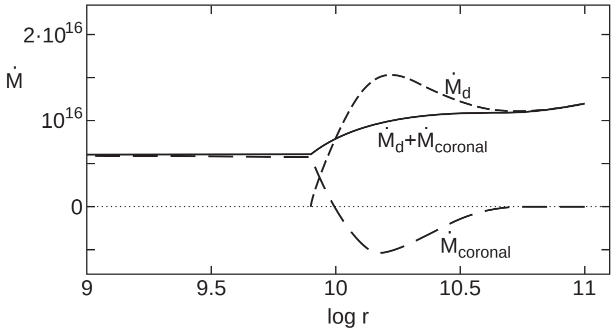

Fig. 4. Disk evolution of A0620, "standard case', with $\dot{M}_{\rm overflow} = 1.9\,10^{-10} M_\odot/{\rm yr}$, mass flow rates 30 years after outburst (compare Fig. 3): $\dot{M}_{\rm d}$ mass flow in the standard cool disk, $\dot{M}_{\rm coronal}$ hot coronal flow and total flow. The negative values for the coronal flow indicate a flow outward (for conservation of angular momentum during disk evolution).

outburst (the value of the critical surface density Σ_A, compare Fig. 3, corresponds to $\alpha_{\rm hot}$=0.3. Note that the viscosity in the hot state used in the ADAF model is not relevant for the modelling of the quiescent phase). We start with an outer disk radius of 9.2 10^{10} cm (geometry connected with the orbital period, secondary mass taken as $0.4 M_\odot$). During the evolution the disk grows to 10^{11} cm. The same code was used as for WZ Sge (solution of the diffusion equation, changes of outer radius due to conservation of mass and angular momentum, evaporation in the inner disk into the coronal flow, changes of the inner edge of the disk, Meyer-Hofmeister et al. (1998)).

3.2. Constraints for the disk evolution

The lightcurve of A620-00 in B magnitude for the outburst in 1917, reconstructed by Eachus et al. (1976), has a shape similar to the lightcurve of the 1975 outburst (Lloyd et al. 1977), indicating that the two outbursts were similar. Though it is not certain that no outburst was missed it is generally assumed that no outburst ocurred in between. Basic constraints on the quiescent disk evolution are then the two facts: (1) the outburst recurrence time of 58 years and (2) the amount of matter stored in the disk and released in the outburst. The amount of energy in the 1975 outburst was estimated as 3-4 10^{44} erg (McClintock et al. 1983, White et al. 1984). This estimate refered to a neutron star primary and to isotropic radiation, a distance of 0.9 kpc was assumed. If we use 1 kpc for the distance as Narayan et al. (1997) and assume a black hole and the disk seen under an inclination of 70° we obtain for the matter accreted in the outburst ΔM= 6–8 10^{24} g (for the inclination see also the newer analysis of Barret et al. 1996).

The total amount of matter is closely related to the rate of mass overflow from the companion star. We study the situation for rates in the range $\dot{M} = 10^{-10} M_\odot/{\rm yr}$ (McClintock et al. 1995) to $2\,10^{-10} M_\odot/{\rm yr}$, the latter corresponding to the results of Narayan et al. (1997). Narayan et al. (1996, 1997) studied the ADAF in A0620-00 in two investigations. The first results from the fit to the spectra were mass flow rates in the disk (assuming that the same rate flows through the outer disk and in the ADAF) of only $7\,10^{-12}$ to $2\,10^{-11} M_\odot/{\rm yr}$ for a primary mass of 4.4 $M_\odot$. But in the second investigation, based on very elaborate calculation techniques and testing different heating of electrons, the resulting mass flow rates in the ADAF for most of the models lie in the range 1 to $1.5\,10^{-10} M_\odot/{\rm yr}$. Most of the models were computed for a primary mass of 6.1 $M_\odot$, but the resulting mass flow rate was about the same for 4.4 $M_\odot$ as taken in the earlier investigation. It was found that nearly all the optical flux comes from the ADAF, the outer disk being quite negligible. From our point of view this means that the mass overflow rate is higher by the additional amount of matter accumulated in the outer disk for the outburst and by the amount lost in the wind when the coronal flow is formed. Our earlier investigations of the evaporation process gave about 20% wind loss (Liu et al. 1995). The mass overflow rate therefore might be as high as $2\,10^{-10} M_\odot/{\rm yr}$. In an earlier investigation (Meyer-Hofmeister & Meyer 1999) first results for an evolution based on a low mass overflow rate were presented.

3.3. Results for disk evolution, standard case

The aim of our computation is to find out whether one can model the disk evolution so that it complies with the constraints on recurrence time and amount of matter stored in the disk $\Delta M$and also agrees with mass flow rate in the ADAF and transition radius derived from the spectral fit by Narayan et al. (1997). Our "standard case' represents such a consistent disk evolution. We take the following parameters: primary mass M_1=4 $M_\odot$, mass overflow rate $1.9\,10^{-10} M_\odot/{\rm yr}$. In Fig. 3 we show the evolution of the thin cool accretion disk with a hot corona above. The onset of the outburst occurs after 59 years. During quiescence the surface density in the disk increases steadily everywhere as the distributions after 15, 30 and 59 years show. The surface density in the outer disk determines the total amount of matter stored at the onset of the outburst ΔM, in our example 6.9 10^{24}g. The transition radius adjusts so that the evaporation rate is the same as the mass flow rate in the inner cool disk (if the transition would occur only in a very narrow radial interval, the evaporation rate and the mass flow rate there would be the same, but in our computations the evaporation of matter into the hot corona is spread out over a transition area). In our standard case we get for the location of the inner edge of the cool disk $r_{\rm trans} = 6.8\,10^9$ cm. In Fig. 4 we show the mass flow in the disk after 30 years of quiescence for the "standard case', a situation comparable to the present state of A0620. 6 10^{15}g/s, half of the overflow rate, flows inward towards the black hole. In the transition region a fraction of the matter flows outward in the corona and condenses again in the cool disk. Such an outward flow is necessary for the conservation of angular momentum in the co-existing cool disk and coronal disk. In the transition region matter is also lost via a wind from the corona. This division of mass flows is about the same over the total computed quiescence evolution.

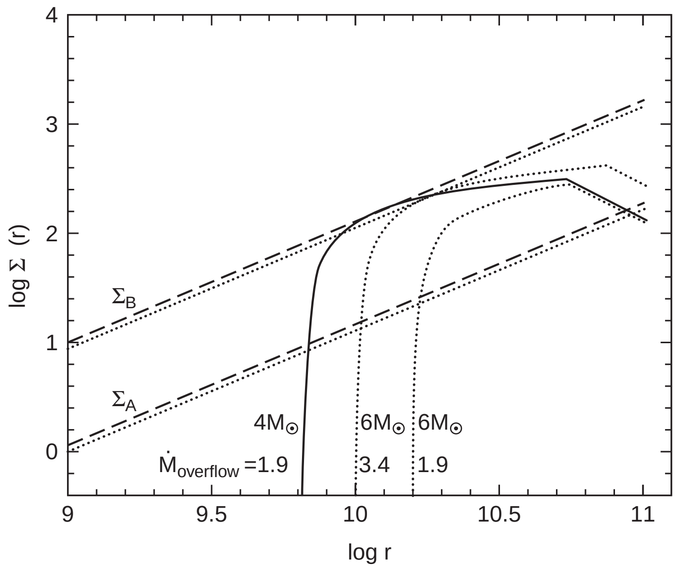

Fig. 5. Comparison of accumulation of matter during quiescence for primary mass 4 and $6M_\odot$, mass overflow rates in $10^{-10}M_\odot/\mathrm{yr}$: solid line surface density distribution at the onset of outburst (same as in Fig. 3), dotted lines onset of outburst for a $6M_\odot$ black hole: due to more efficient evaporation the hole is larger and a higher mass overflow rate $3.4\,10^{-10}M_\odot/\mathrm{yr}$ instead of $1.9\,10^{-10}M_\odot/\mathrm{yr}$ is needed to produce an outburst (in our example after 55 years). The low rate of $1.9\,10^{-10}M_\odot/\mathrm{yr}$ would lead to a stationary disk without an outburst.

3.4. Results for disk evolution, variation of mass overflow rate and viscosity

We also studied the disk evolution for other parameters. The smaller the rate $\dot M_{\mathrm{overflow}}$ the more time is needed to accumulate enough matter to reach the critical surface density Σ_{B}. The balance of mass flow in the disk and evaporation determines the transition radius. A lower rate $\dot M_{\mathrm{overflow}}$ results in a more extended hole (compare Fig. 2, upper panel) and the critical surface density can then only be reached farther out in the disk. This means the surface density is higher everywhere in the disk and therefore more matter piles up in the outer disk. The quiescence lasts longer. We found that for an overflow rate of $1.8\,10^{-10}M_\odot/\mathrm{yr}$, only a little lower than in our standard case, no outburst occurs anymore and the disk is stationary. Such a system would not easily be recognized. On the other hand a slightly higher rate triggers the outburst early (see Table 1). For a slightly higher viscosity parameter α_{cool}=0.06 the accumulated amount of matter ΔM is less and the recurrence time is shorter than for the standard value 0.05. (Small variation of the parameters within the allowed range would lead to exact agreement with the observed recurrence time).

3.5. Results for disk evolution, more massive primary star

For higher primary mass the evaporation is more efficient (compare Fig. 2, lower panel). The transition radius is larger. A higher mass overflow rate is necessary to compensate for this. Assuming a black hole of $6\,M_\odot$ and a rate of $3.4\,10^{-10}M_\odot/\mathrm{yr}$ we get an outburst after 55 years. Almost twice as much matter is stored in the disk compared to the "standard case" with the $4\,M_\odot$ black hole. In Fig. 5 we show the distribution of surface density at the onset of the outburst for 4 and 6 $M_\odot$ together with the slightly different critical surface densities for these primary masses. The rate adequate for the triggering of the outburst for $4\,M_\odot$ would only give a stationary disk for $6\,M_\odot$, far from an instability. For an even more massive primary of 12 $M_\odot$ a very high mass overflow rate would be necessary to reach an outburst. This would not agree with the constraints for A0620, but might be the case for other black hole systems.

Table 1. Parameters of models of A0620

model	M_1	α_{cool}	$\dot M_{\mathrm{overflow}}$	recurrence time	ΔM	r_{trans}
	$[M_\odot]$		$[10^{-10}\frac{M_\odot}{\mathrm{yr}}]$	[yr]	$[10^{24}\mathrm{g}]$	$[10^9\mathrm{cm}]$
1a			1.8	stationary	6.9	7.6
1b	4	0.05	1.9	59	6.9	6.8
1c			2.0	44	6.9	6.5
2a			1.8	stationary	5.7	7.6
2b	4	0.06	1.9	50	5.8	7.0
2c			2.0	38	5.9	6.6
3a			3.0	stationary	12.3	10.7
3b	6	0.05	3.2	112	13.1	9.7
3c			3.4	55	13.1	9.9

4. Comparison of the results from disk evolution with the results from the ADAF model

In Table 2 we summarize the comparison of the results from our disk evolution computations and the results from the spectral fit of the ADAF model to the observations. The transition radius $r_{\mathrm{trans}}(\mathrm{H}_\alpha)$ used for the ADAF fit is estimated from observations on the basis of the largest velocity $v_{\max}$ seen in the H_α line, 2100 $\mathrm{km s}^{-1}$ (Marsh et al. 1994, Orosz et al. 1994). For the inclinations $70°$ and $55°$ and the related black hole masses the values r_{trans} follow, the smaller value for the smaller inclination and higher primary mass. The ADAF fit yields a mass flow rate $\dot M_{\mathrm{ADAF}}$. This result does not depend sensitively on r_{trans}. Our computations are carried out for two values of viscosity, α_{cool}=0.05, the standard value from dwarf nova outburst modelling and 0.06. We take 4 and $6M_\odot$ for the primary mass. We consider only cases of disk evolution which comply with the constraints (1) recurrence time of 59 years of A0620 and (2) amount of matter accumulated for the outburst in agreement with the outburst energy (only a rough value). For $6M_\odot$ the second constraint is less well met. The flux measurements used for the ADAF fit were obtained many years apart as pointed out by Narayan et al. (1996). For our models 1b and 3b (compare Table 1) we therefore give the transition radius and the coronal mass flow rate (as supply for the ADAF) for the evolutionary times of 20 and 30 years after the outburst. This documents the change of values during evolution. Comparing the rates $\dot M_{\mathrm{ADAF}}$ and $\dot M_{\mathrm{coronal}}$ the values are closer for the $6M_\odot$ primary. But we

Table 2. Comparison of the results from disk evolution with the transition radius from the H_α emission lines and the mass accretion rate in the ADAF.

M_1	$4.4 M_\odot$	$6.1 M_\odot$
$\log r_{\rm trans}/{\rm cm}\,(H_\alpha)$	10.12	10.06
$\dot M_{ADAF}$*	$1.45\times10^{-10}\,\frac{M_\odot}{\rm yr}$	$1.31\times10^{-10}\,\frac{M_\odot}{\rm yr}$
M_1	$4 M_\odot$	$6 M_\odot$
$\log r_{\rm trans}/{\rm cm}$ (disk evolution **)	10.0 to 9.9	10.2 to 10.1
$\dot M_{\rm coronal}$ (disk evolution **)	0.8 to $1.1\times10^{-10}\,\frac{M_\odot}{\rm yr}$	1.2 to $1.6\times10^{-10}\,\frac{M_\odot}{\rm yr}$

* models 1 and 3 of Narayan et al. (1997)
** models 1b and 3b (c.f. Table 1), values 20 to 30 years after outburst

have mentioned already that in this case somewhat more matter is accumulated than estimated from the outburst energy. Keeping in mind that here the results are brought together from very different physical processes, (a) the radiation from the innermost very hot sphere and (b) the evolution of the cool disk with evaporation of matter into a coronal layer, the derived rates $\dot M_{\rm ADAF}$ and $\dot M_{\rm coronal}$ are remarkably similar.

5. General features of the ADAF formation and conclusions

The computation of the disk evolution for a set of parameters allows us to learn about the general features of the transition of the cool disk to a coronal disk.

5.1. Location of the transition

As pointed out in Sect. 2 the transition radius is determined by the balance of mass flow in the disk and evaporation. This situation is the same in disks around white dwarfs and around black holes. In dwarf nova systems for a high mass flow rate, the transition radius might move in to the white dwarf surface or even disappear. Then no hole is created in the disk but evaporation still goes on continuously. In disks around black holes, as for example in A0620, for the low accretion rates in quiescence a transition at a distance of about 10^{10} cm from the black hole results.

The transition radius can be estimated without following the disk evolution if one assumes a mass flow rate in the disk. But the evaluation of radii together with the disk evolution includes the constraints on the evolution and is therefore more firm. Taking the transition radius and the rate $\dot M_{\rm ADAF}$ and calculating the evaporation rate one can compare these results. This was done in the investigations of Meyer (1999) and also by Liu et al. (1999). In the latter work this comparison was also performed for advection-dominated accretion flows onto massive black holes in galactic nuclei.

5.2. The relation between the mass overflow rate and the mass flow rate in the corona

For the ADAF fit it was assumed that the mass flow rate in the outer cool disk and in the inner very hot spherical region would be the same. Since Narayan et al. (1997) found that most of the optical light also originates in the ADAF the mass flow rate in the outer disk is not important for the spectrum. But it is of interest to find out what the mass overflow rate from the companion star is; in our best example (model 1b) it is $1.9\,10^{-10} M_\odot/{\rm yr}$. This raises interesting questions about the nature of the magnetic braking mechanism in this binary (for a discussion see King et al. 1996 and Menou et al. 1999a).

From our computations we find that, rather independent of the time passed after the last outburst, about 1/3 of the matter flowing over from the secondary is stored in the outer disk for the next outburst. The other 2/3 is evaporated into the corona. From this amount 20% is lost in a wind and the remaining 80% flows

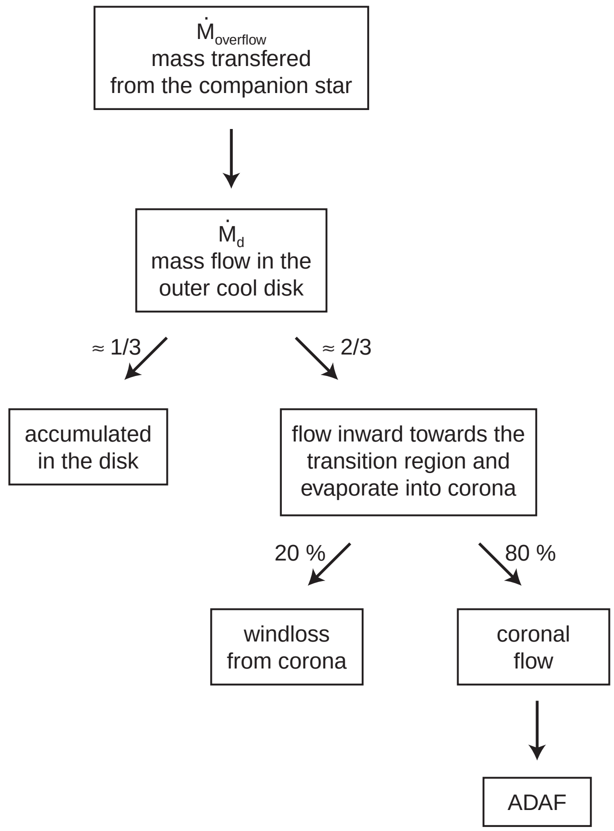

Fig. 6. Rate of the advection dominated accretion flow resulting from mass transfer from the companion star, model for A0620

inward in the corona and provides the matter for the ADAF in the very hot inner region close to the black hole. This means that about half of the matter flowing over from the companion star accretes onto the black hole in quiescence. In Fig. 6 we show this division of the flow of matter in the cool standard disk and the corona.

5.3. Outbursts of X-ray transients

Our results for disk evolution show (compare Table 1) that small changes in the mass overflow rate from the companion star affect the outburst recurrence time essentially. For rates only slightly less than the rate which provides the onset of instability after 59 years (example A0620-00) the critical surface density can not be reached, the system is globally stable. Probably many such systems exist, faint persistent soft X-ray binaries.

References

Asai K., Dotani T., Hoshi R., et al., 1998, PASJ 50, 611
Barret D., McClintock J.E., Grindlay J.E., 1996, ApJ 473, 963
Cannizzo J.K., 1998, ApJ 494, 366
Eachus L.J., Wright E.L., Liller W., 1976, ApJ 203, L17
Elvis M., Page C.G., Pounds K.A., et al., 1975, Nat 257, 656
Esin A.A., McClintock J.E, Narayan R., 1997, ApJ 489, 865
Huang M., Wheeler J.C., 1989, ApJ 343, 229
Illarionov A.F., Sunyaev R.A., 1975, A&A 39, 185
King A.R., Kolb U., Burderi L., 1996, ApJ 464, L127
Kuulkers E., 1998, New Astronomy Reviews 42, 1
Kuulkers E., 1999, In: Mineshige S., Wheeler J.C. (eds.) Proc. of Disk Instablities in Close Binary Systems. Universal Academic Press, Kyoto, p. 169
Lasota J.-P., Narayan R., Yi I., 1996, A&A 314, 813
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, submitted to ApJ
Liu F.K., Meyer F., Meyer-Hofmeister E., 1995, A&A 300, 823
Lloyd C., Noble R., Penston M.V., 1977, MNRAS 179, 675
Marsh T.R., Robinson E.L., Wood J.H., 1994, MNRAS 266, 137
McClintock J.E., Petro L.D., Remillard R.A., Ricker G.R., 1983, ApJ 226, L27
McClintock J.E., Remillard R.A., 1990, BAAS 21, 1206
McClintock J.E., Horne K., Remillard R.A., 1995, ApJ 442, 358
Menou K., Narayan R., Lasota J.-P., 1999a, ApJ 513, 811
Menou K., Esin A., Narayan R., et al., 1999b, ApJ (in press)
Meyer F., 1999, In: Mineshige S., Wheeler J.C. (eds.) Proc. of Disk Instablities in Close Binary Systems. Universal Academic Press, Kyoto, p. 209
Meyer F., Meyer-Hofmeister E., 1994, A&A 288, 175
Meyer-Hofmeister E., Meyer, 1999, In: Mineshige S., Wheeler J.C. (eds.) Proc. of Disk Instablities in Close Binary Systems. Universal Academic Press, Kyoto, p. 217
Meyer-Hofmeister E., Meyer F., Liu B.F., 1998, A&A 339
Mineshige S., Wheeler J.C., 1989, ApJ 343, 241
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., 1999, in: Abramowics M.A., et al. (eds.) The Theory of lack Hole Accretion Discs. Cambridge University Press
Orosz J.A., Bailyn C.D., Remillard R.A., 1994, ApJ 436, 848
Ritter H., Kolb U., 1998, A&AS 129, 83
Shakura N.I., Sunyaev R.A., 1973, A&A 24, 337, 1995, ApJ 446, 741
Tanaka Y., Shibazaki N., 1996, ARA&A 34, 607
van Paradijs J., McClintock J.E., 1995, In: Lewin W.H.G., van Paradijs J., van Heuvel E.P.J. (eds.) X-Ray Binaries. Cambridge Univ. Press, p. 58
White N.E., Kaluziewski J.L., Swank J.H., 1984, In: Woosley S.E. (ed.) High Energy Transients in Astrophysics. AIP Conference Proc. 115, AIP, New York, p. 31