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A limit for the mass transfer rate in soft X-ray transients

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Abstract. Many black hole X-ray transients are in a low state for several decades until an outburst occurs. We interpret this outburst behaviour as a marginal occurrence of a dwarf nova type disk instability in the cool outer accretion disk. We compute the disk evolution including evaporation of matter from the cool thin disk. This evaporation process causes the transition to a hot coronal flow. The efficiency depends on the black hole mass.

The new results are the dependence of the outburst recurrence time on the mass transfer rate from the companion star and the fraction of the matter which is accumulated in the disk for the outburst. We determine a lower limit of the mass transfer rate, below which no disk instability can be triggered. We find that for rates slightly lower than those in the known black hole X-ray transients the disk would be stationary. We argue that many such optically faint black hole X-ray binaries with stationary cool accretion disks exist.

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

1. Introduction

Transient X-ray binaries containing a black hole form two different classes of objects, the high-mass and the low-mass binaries. The high-mass systems have an O or B star companion and the observations indicate mass transfer at a high rate onto the black hole primary. The low-mass systems, known as soft X-ray transients (SXT) or X-ray novae have a K or M dwarf companion. The Roche-lobe filling low-mass star transfers matter via an accretion disk onto the compact star. These binaries exhibit outbursts, usually detected in X-rays.

The transient sources are interesting objects to study the accretion disk. Already a decade ago Huang & Wheeler (1989) and Mineshige & Wheeler (1989) argued that the rare outbursts are caused by a disk instability as in dwarf nova systems where the primary star is a white dwarf. Recently detailed modelling of the decline of the outburst lightcurve was done; for a comprehensive study and an overview see Cannizzo (1998,1999).

Observational data for X-ray novae and system parameters deduced from the observations are summarized in reviews by Tanaka & Shibazaki (1996) and Tanaka (1999). Chen et al. (1997) carried out a statistical study of all long-term X-ray and optical lightcurves. Asai et al. (1998) investigated nine black hole X-ray transients in the quiescent state. If we compare SXTs with dwarf novae (Kuulkers 1999) we especially notice the long outburst recurrence times. The primary stars are black holes or neutron stars, and the orbital periods are longer. Only a few dwarf novae with very short orbital periods have such long recurrence times, connected with a high outburst amplitude. These systems are known as "tremendous outburst amplitude dwarf novae", TOADs (Howell et al. 1995). For the best observed system, WZ Sagittae, with outbursts every 31 years, the amount of matter accumulated in the disk for the outburst is about 1-2 10^{24}g (Smak 1993), a factor of only about 3 smaller than that estimated for the transient source A0620-00 (McClintock et al. 1983). But there is one important difference between WZ Sge stars and SXTs: the size of the disk in WZ Sge with an orbital period of only 81.6 minutes is much smaller than those in SXTs with typical periods of several days. The viscosity parameter in the disk in WZ Sge therefore has to be a factor of 10 to 100 lower if the same amount of matter is accommodated in the much smaller area (Meyer-Hofmeister et al. 1998).

We want to point out another feature, different in dwarf novae and SXTs, but essential for the state of the disk. In transient sources and dwarf novae in quiescence the outer accretion disk is cool and matter is accumulated for the outburst. In dwarf novae such a disk is cool everywhere from the outer to the inner edge. In black hole transient sources, the disk can reach inward to the vicinity of the black hole. At such close distance a disk is hot even

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for very low mass flow rates. Since hot and cool disk regions cannot remain stationary side by side (Meyer 1981), transition fronts will sweep back and forth over the disk leading to a rapid sequence of hot and cool states preventing any long-term quiescent accumulation of mass in the disk. To circumvent this problem one either has to assume an extremely low viscosity so that matter cannot flow towards the inner disk (in contradiction to the amount of matter accumulated for a SXT outburst) or a hole in the inner thin disk due to evaporation. Our computation of disk evolution includes evaporation into a coronal flow and the co-existence of thin disk and corona consistently. Since in quiescence about half of the matter flows through the corona evaporation is an essential feature in the evolution of SXTs. The spectra of quiescent SXTs are not consistent with an accretion disk model of a thin disk reaching inward to the black hole, as pointed out by McClintock et al. (1995) and Narayan et al. (1996), but the problem can be resolved by accretion via an ADAF which is the inward continuation of the coronal evaporation flow (for a review see Narayan et al. 1999).

The observed outburst recurrence time of transient sources ranges from around one year to several decades, for many systems only one outburst is recorded. We show in our investigation that the outbursts may be triggered only marginally and the recurrence time then can vary very significantly for a small difference in mass transfer rates. For slightly lower mass overflow rates from the companion star the systems remain in a stationary state with a cool disk. The question whether such faint non-transient black hole binaries exist was also approached, in a different way, in connection with the physics of an advection-dominated accretion flow (ADAF) by Menou et al. (1999b). The answer depends on the expected mass overflow rates in these binaries. But the predictions of the rates caused by magnetic braking are so uncertain that one can better draw conclusions from the outburst behavior of SXTs on the efficiency of magnetic braking than vice versa.

In Table 1 we summarize properties of transient sources. Listed are binaries for which the observations document that the compact star is a black hole. In addition to these systems there exist a number of transients which are probably also black hole binaries, but also for those only in a few cases is more than one outburst known.

In our investigation we discuss the following points. We describe the computational code for evolution of the disk in quiescence including evaporation of the inner disk in Sect. 2. In Sect. 3 we show the results: the outburst recurrence time depends strongly on the black hole mass, the amount of matter accumulated in the disk during quiescence, and the fraction of mass accumulated to mass transferred from the companion star. We determine the lower limit for the overflow rate to trigger a disk instability. In Sect. 4 we discuss the regime of faint non-transient black hole low mass X-ray binaries. Conclusions follow in Sect. 5.

2. Evolution of the disk in quiescence, interaction of cool disk and hot corona

The evolution of accretion disks in binaries is governed by the frictional diffusion of angular momentum. Conservation of mass and angular momentum give the diffusion equation. The matter transferred from the companion star accretes via the disk onto the primary star. At the same time angular momentum is transported outward in the disk. We consider a geometrically thin disk with a corona above the inner part of the thin disk. The corona originates from evaporation of matter from the cool thin disk in a "siphon-flow" process (Meyer & Meyer-Hofmeister 1994). Conservation of mass and angular momentum has to be considered in the thin disk and the corona together. To compute the evolution of disk plus corona we solve the diffusion equation for the change of surface density in the cool disk with an additional term for the mass and angular momentum exchange with the corona above.

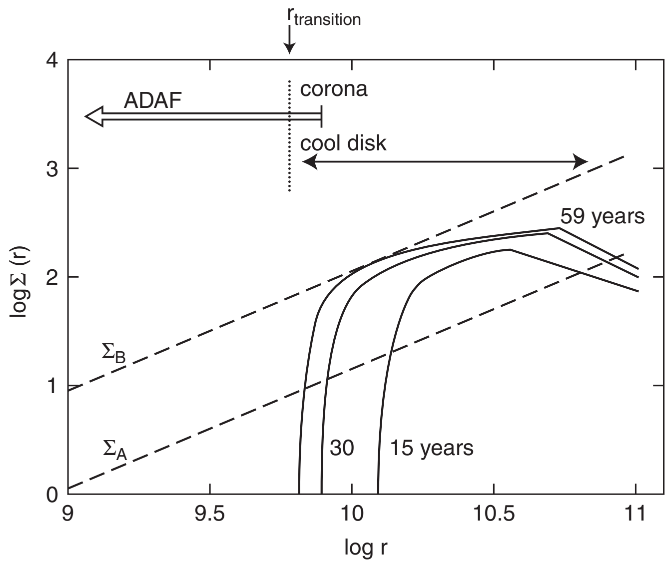

Fig. 1. Disk evolution of A0620, accumulation of matter in quiescence. Σ_A and Σ_B are critical surface densities. For the surface densities between these values two states, hot and cold, are possible. When accumulation of matter reaches Σ_B an outburst sets in (from Meyer-Hofmeister & Meyer 1999b, Fig. 3)

The boundary conditions at the inner and outer edge of the disk are the following. The outer disk radius cannot grow above a cut-off radius where either tidally induced shocks or the eccentric disk instability (3:1 resonance between Kepler binary period and Kepler rotation in the disk (Whitehurst 1988, Lubow 1991)) transfer any surplus of angular momentum outflow in the disk to the orbit. For low mass ratios M_1/M_2, as in the binaries with a black hole primary and a low mass star secondary, the 3:1 resonance radius lies inside the tidal truncation radius and determines the cut-off. If the disk radius is inside this ra-

Table 1. Black–hole transient sources

Source name		BH mass ($M_\odot$)	Companion star	orbital period (h)	outburst year	rec. time Δt (ys)	acc. matter log M_d	Ref.
J0422+32	XNova Per	>3.2	M 2 V	5.09	'92	>30	23.9	1
0620-003	XNova Mon	>7.3	K 5 V	7.75	'17,'75	58	24.6	2
1124-684	XNova Mus	~ 6	K 0-4 V	10.4	'91	>30	25.3	3
1543-475	XN '71,'83,92	2.7-7.5	A 2 V	26.95	'71,'83,'92	≈ 10	25.1('92)	4
J1655-40	XNova Sco	7.02±0.22	F 3-6	62.7	'94	>30	23.7	5
1705-250	XNova Oph'77	~ 6	K$\sim$ 3 V	12.51	'77	>30	24.5	6
2000-251	XNova Vul	6-7.5	early K	8.26	'92	>30	25.1	7
2023-338	XNova Cyg	8-15.5	K 0 IV	155.4	'38,'56,'79,'89	10-20	25.8('89)	8

Note: Systems established as black hole transients, data for black hole mass, spectral type of companion star, orbital period, outburst year and list of references from Tanaka & Shibazaki (1996), recently established also Nova Ophiuchi 1977 and 4U 1543-47. Amount of matter accumulated $log M_d$ derived from data collected by Chen et al. (1997).
References: (1) Filippenko et al. 1995a, (2) McClintock & Remillard 1986, (3) McClintock et al. 1992, (4) Orosz et al. 1998, (5) Orosz & Bailyn 1997, (6) Remillard et al. 1996, (7) Filippenko et al. 1995b, (8) Casares et al. 1992.

dius, it constitutes a free boundary where the diffusion between mass and angular momentum flows in the impinging stream and in the disk determines its growth or decline. The inner edge of the thin disk is reached where the coronal flow via evaporation has picked up all mass flow brought in in the thin disk. Evaporation determines how mass and angular momentum flow in the disk tend to zero at this boundary. This results in a thin disk boundary condition. Farther in only the coronal flow exists. The diffusion equation for the cool disk with a corona above and the appropriate boundary conditions were first derived for a dwarf nova accretion disk around a white dwarf (Liu et al. 1997, Meyer-Hofmeister et al. 1998), then used also for disk around black holes (Meyer-Hofmeister & Meyer 1999a).

2.1. Computational method

We followed the evolution of the cool accretion disk with the hot corona above. We took primary star masses of 4 to 12 $M_\odot$, binary orbital periods from 4 to 16 hour and mass overflow rates of several $10^{-10} M_\odot$/yr to simulate the situation in SXTs. To solve the diffusion equation we used the viscosity-surface density relation from Ludwig et al. (1994) and for the viscosity parameter (Shakura & Sunyaev 1973) of the cool state we took the value $\alpha_{\rm cool}$=0.05. It is interesting that a value usually taken for dwarf nova instability modelling also allows a successful modelling of the SXT outburst intervals.

As mentioned above, for the low mass ratio SXTs the disk size is limited by the 3:1 resonance radius. This radius does not depend on the secondary mass, it is determined only by the assumed primary mass and period. For the initial size of the disk we assume 90% of this 3:1 resonance radius. In our calculations, the initial disk quickly expands to the limiting size and the evolution becomes independent of the value of the mass ratio. Only for the very early phase the specific angular momentum of the matter transferred from the secondary has some effect on the evolution. For low mass ratios it depends only weakly on the mass ratio. For convenience we took a secondary mass according to a Roche-lobe filling main-sequence star. The secondaries could be evolved (as for example indicated for A0620-00 with its K5V companion) resulting in a smaller mass (King et al. 1996). The effect on our results is very small.

We take evaporation into account using a scaling law for the rate $\dot M_{\rm ev}$

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

with M_1 primary mass, r distance to the primary (Liu et al. 1995). We assume that immediately after the decline from the long lasting outburst the surface density initially is very low everywhere in the disk. This seems adequate for long recurrence times. For short recurrence times this might not be a good approximation. But we include these latter systems only to show the trend for higher mass overflow rates.

3. Results of computations and comparison with observations

3.1. General features of disk evolution

During the early evolution after an outburst the surface density distribution in the cool disk is low and the thin disk is in the cool state. Matter flows continuously over from the companion star. A part of this matter is accumulated in the cool disk, a part flows through the thin disk inward and is evaporated in the disk region near the inner edge where evaporation is most efficient. During the formation of the coronal flow wind loss occurs, so that only about 80% of the matter evaporated out of the cool disk yields the mass supply for the advection-dominated accretion flow (ADAF) towards the black hole. The evolution of the thin outer disk proceeds until the surface density reaches the critical value beyond which no cool state of the disk is possible anymore. The limiting surface density depends on the values chosen for the disk viscosity parametrization. An example is the modelling of the SXT A0620-00 (Meyer-Hofmeister & Meyer 1999b), the accumulation of matter in the disk is shown in Fig. 2.

3.2. Recurrence time of outbursts

In Fig. 2 we show the outburst recurrence time found for the evolution of disks around black holes of 4, 8 and 12 $M_\odot$. The interesting result is the effect of the black hole mass. This can be understood in the following way. The higher evaporation efficiency for higher primary mass leads to the formation of a more extended inner disk hole. If the hole is more extended, matter is accumulated in further outward geometrically larger disk regions. To reach the critical surface density for the disk instability there definitely requires the accumulation of more matter. This means higher mass overflow rates are necessary to trigger an outburst within the same recurrence time. This feature already became clear in the modelling of the accretion disk in A0620-00 assuming primary masses of 4 or 6 $M_\odot$ (Meyer-Hofmeister & Meyer 1999b, Fig. 5). If the outbursts are triggered only marginally an analytical calculation of the recurrence time (Menou et al. 1999b) is not possible anymore.

We study the disk evolution for different orbital periods. A longer period means that the disk is larger. If the mass transfer rate is close to the value for which outbursts are triggered only marginally, most of the matter flows through the cool disk and the size of the disk does not influence the disk evolution anymore.

Our computations establish a lower limit for the mass overflow rate in order that a dwarf nova type instability in the accretion disk can occur, i.e. that the system is a transient source. The question arises how many systems might have mass transfer rates below this limit.

3.3. Accumulated matter in the disk

Our computations of disk evolution give both the amount of matter accumulated in the disk until the next outburst is triggered and also how much matter was accreted onto the black hole during this time. Accumulation of matter in the disk means that everywhere in the disk between inner and outer edge the surface density rises continuously during quiescence (see for example Fig. 3 in Meyer-Hofmeister & Meyer 1999b).

Our computations yield the following. For given black hole mass and orbital period the value M_d depends slightly on the mass transfer rate. For a low mass transfer rate $\dot{M}_T$, i.e. an only marginally unstable disk, most matter flows through the disk (for a stable disk all matter flows through).The total amount of accumulated mass is low. A somewhat higher mass transfer rate leads to a higher value M_d. For relatively high transfer rates the outburst then occurs earlier and again less mass in accumulated. This means M_d as a function of $\dot{M}_T$ has a maximum for a certain transfer rate; but for all cases, considered here, recurrence time $\geq$ 10 years, the values lie in a narrow range. In Fig. 3 we show this range of M_d.

As discussed in connection with the outburst recurrence time the amount of matter accumulated increases with the primary mass due to the more extended inner hole and the accumulation in outer larger disk regions. In Fig. 3 we show our results for two primary masses and for different orbital periods of the binaries. The amount of matter is higher for longer orbital periods because of the larger disks. It is remarkable that for a given black hole mass and orbital period, the total amount of matter in the disk varies only within a narrow range shown in Fig. 3, for a wide variation of the recurrence time.

The theoretically determined amount of matter M_d can be compared with observations. In Table 1 we list the values derived by Chen et al. (1997), in general accurate to about a factor of 2-3. Except for the two systems J0422+32 and J1655-40 our theoretically derived values and those from observations agree. For J0422+32 the estimated black hole mass is relatively low, which should be related to a lower value M_d as shown in Fig. 3. As already pointed out by Menou et al. (1999b) for J1655-40 several complications appear in the determination of the value M_d. Note that the highest value was found for the particularly extended disk of GS2023+338 with the long orbital period of 155 days.

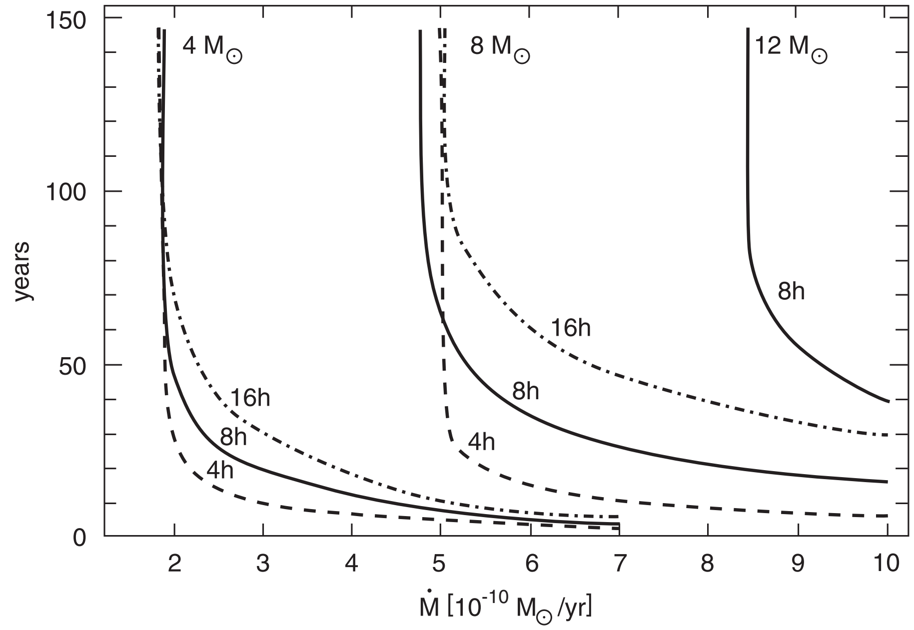

Fig. 2. Computed outburst recurrence time for different black hole masses and orbital periods of the binary as a function of the mass transfer rate $\dot{M}_T$ from the companion star. Note that the recurrence time increases steeply with decreasing $\dot{M}_T$ as the situation of only marginal triggering of the disk instability is approached. For even lower rates the disk is stable.

The amount of matter in the disk is connected with the viscosity parameter for the cool disk. The agreement with observations confirms that the chosen value 0.05 is adequate and documents the similarity with dwarf nova accretion disks.

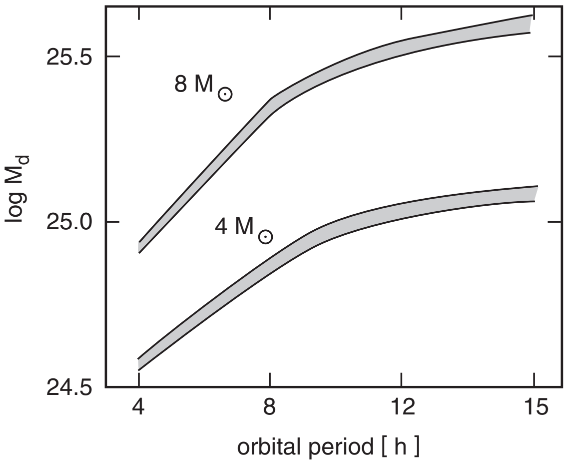

Fig. 3. Amount of matter M_d accumulated in the accretion disk for systems with an outburst reccurrence time of ≥ 10 years. The amount depends slightly on the mass tranfer rate, we give a range of values (see text for detail).

3.4. The proportion of mass accumulated in quiescence

An interesting result is also what fraction of the matter transferred from the companion star is actually accumulated in the disk. For an orbital period of 8 hours we show in Fig. 4 the fraction $\langle \dot{M}_{\rm acc} \rangle / \dot{M}_T$ as a function of the recurrence time. Here $\langle \dot{M}_{\rm acc} \rangle$ is the average value over the total quiescence (recurrence time). As can be seen from Fig. 3, the amount of accumulated matter is always about the same no matter how long the recurrence time is. Therefore the fraction $\langle \dot{M}_{\rm acc} \rangle / \dot{M}_T$ decreases when the outbursts occur more rarely. If the transfer rate is so low that outbursts do occur only marginally almost all matter flows through the disk, the fraction approaches zero.

The fraction is almost the same for 4 and $8 M_\odot$. This arises from two facts which compensate: (1) about three times more matter is accumulated for the more massive black hole (see Fig. 3), (2) the rates necessary to trigger an outburst after a given time interval are larger by about the same factor (see Fig. 2). For typical black hole masses and a recurrence time of about 50 years our computations yield the value 35 to 40 %. This means 60 to 65% of the matter change to the coronal flow towards the black hole. About 1/5 of this flow is removed by wind loss from the corona. Menou et al. (1999b) studied the total mass flow rate in the disks of SXTs. They took the mass flow rate towards the black hole in quiescence from fits of the observed spectra based on the ADAF model and the rate of average accumulated matter from the total outburst energy for each system. They came to the conclusion that the amount which flows through the disk is comparable or larger than the accumulated amount, in agreement with our results of disk evolution modelling.

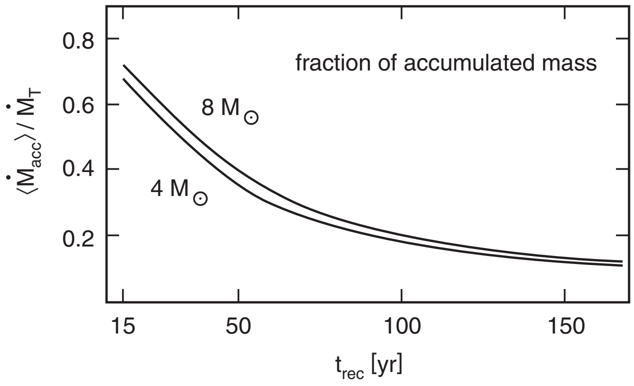

Fig. 4. Fraction of matter accumulated in the disk (average over recurrence time) to matter transferred from the companion star $\langle \dot{M}_{\rm acc} \rangle / \dot{M}_T$ as a function of the recurrence time $t_{\rm rec}$ (orbital period 8 hours).

4. Stationary systems

As shown in Fig. 2, for each assumed primary mass there exists a limiting mass transfer rate for which the recurrence time approaches infinity. For rates below no outburst can be triggered, the accretion disk is stationary. All matter transferred from the companion star flows through the disk, changes to a coronal flow (except for the wind loss) and forms an ADAF. Such systems are very faint, only recognizable from their radiation in X-rays from the innermost region around the black hole primary. How many systems of this kind may exist? The answer depends on the mass transfer rates in these systems and therefore on the angular momentum loss expected for these systems during their secular evolution.

King and collaborators (King et al. 1996, 1997) discussed the angular momentum losses caused by magnetic braking in black hole binaries and the question of whether the expected mass transfer rates let the systems appear as transient sources. Assuming unevolved main-sequence companion stars they got, based on magnetic braking rates of Verbunt & Zwaan (1981), mass transfer rates so high that one would instead expect to find binaries with disks in a permanent hot state. Using the form of Mestel & Spruit (1987) leads to somewhat smaller but still high rates. That means the disk is hot everywhere out to the outer edge. For this evaluation the location of the inner edge of the disk is unimportant.

High mass X-ray black hole binaries as Cyg X-1, LMC X-1 and LMC X-3 with O or B star companions have mass flow rates high enough to avoid the disk instability. Two very bright hard X-ray sources in the Galactic center region, the black hole candidates GRS 1758-258 and 1E1740.7-2942 with spectra similar to Cyg X-1 in the low state were detected by SIGMA during most of the observations in 1990 to 1998 (Kuznetsov et al. 1999). But optical data indicate a companion star mass of about $\leq 4 M_\odot$ (Chen et al. 1994). If this is the case these systems would be low-mass black hole binaries in a persistent state.

For rates slightly below the upper critical rate we expect outbursts with a short repetition time, hundreds of days, as observed for example about 460 days for GX 339-4, or 600 days for 1630-472RN (Tanaka & Lewin 1995, van Paradijs 1995). But this situation is not described well with our modelling; it would be necessary to follow the complete outburst cycles. Trudolyubov et al. (1998) argued that the occurrence of four successive outbursts of GX 339-4 in 1990 to 1994 might be connected with an increase of the mass transfer from the companion star due to irradiation.

Menou et al. (1999b) approached the question of whether a population of faint non-transient low mass black hole binaries exists. For this investigation the location of the inner edge is important, because the instability would be triggered there. The radius of transition $r_{\rm tr}$ from the thin disk to a hot flow was estimated combining three concepts, constraints from the stream dynamics $r_{\rm tr} \leq$ the impact radius of the stream in the disk), from the observed H_α emission line width (provides an upper limit to the speed of matter in the disk, therefore to the inner edge position) and the maximum radius where an ADAF is possible. The total mass flow rate in the disk was deduced from the rate of accretion in the innermost disk (from spectral fitting of the ADAF) together with a rate of average accumulation (derived from the outburst energy). The analysis was performed for the systems with best data, which we also used. The conclusion was that for the evaluated total mass flow rate the disks in black hole SXTs truncated at $r_{\rm tr}$ are unstable and will undergo the thermal-viscous instability. Our detailed computations including evaporation give the location of the inner disk edge at every time of the evolution, and take the actual mass flow rate in the inner disk in account, so that the question whether an outburst is triggered can be answered immediately for different black hole masses and different mass transfer rates from the companion star. Menou et al. (1999b) argued that magnetic braking could not be the cause for the mass transfer since the values would be too high. This is true for unevolved companion stars. But if the companion star is evolved, its mass may be only about half of that of a Roche-lobe filling main-sequence star (King et al. 1996) and the rates would be lower by a factor of about 1/5. The lower rates would come down to about the values for transient behaviour.

5. Conclusions

Our investigation gives new insight into the evolution of the disks in black hole X-ray transients. At the same time new questions also arise.

5.1. The occurrence of outbursts

We follow the disk evolution including evaporation into a coronal flow. Conclusions on stability are only possible if one considers these truncated disks where at a certain radius $r_{\rm tr}$ the thin accretion disk ends and the accretion changes to the form of a hot coronal flow. The outbursts are caused by the thermal-viscous instability as in dwarf novae, modelled with a viscosity value suitable for dwarf nova outbursts, which confirms the similarity.

We found that the dependence of the evaporation process on the black hole mass essentially determines the outburst cycles. If the black hole mass is higher, a higher mass transfer rate is needed to trigger an outburst after a certain time interval of accumulation of matter. For example to get a recurrence time of 30 years for 4 or 8 $M_\odot$ black holes about 2.5 or 6.5 $10^{-10}M_\odot$/yr respectively are needed (compare Fig. 2). The outburst after long quiescence can be understood as marginal triggering of the disk instability. In such a case a small difference in the mass transfer rate results in an large change of the recurrence time.

The location of the inner edge of the thin disk is important for the outburst cycles. In our modelling $r_{\rm tr}$ follows from the evaporation model. The chosen viscosity parameter $\alpha_{\rm cool}$ also influences the result, but this not a free parameter because the total amount of accumulated matter has a constraint from the outburst energy.

The systems listed in Table 1 are the best observed sources with the black hole mass established from observations. Assuming that no outburst was missed during the 30 years of X-ray observations (for a discussion see Chen et al. 1997) the recurrence times might be very long. In our view the instability is marginally triggered in these sources. For only a little lower rates these systems would be stationary, all matter transferred from the companion star steadily flows towards the black hole (wind loss excepted). Being so close to the marginal state in several black hole binaries, one expects a large number of similar systems in permanent quiescence. Such sources are very faint, with a spectrum like SXTs in quiescence. Menou et al. (1999b) discussed the observational signatures of such faint persistent black hole low-mass X-ray binaries.

5.2. Mass transfer rates

Our computations of disk evolution to model the observations confirm that mass transfer rates of 10^{-10} to $10^{-9}M_\odot$/yr cause the transient behaviour (with a strong dependence on the black hole mass). These rates agree with the estimates for the amount of accumulated matter and with the rates derived from the spectral fits based on the ADAF model (Narayan et al. 1996, 1997, for a review see Narayan et al. 1999). For the accretion in disks around black holes we get a consistent description with the thin outer disk and the change to a coronal flow due to evaporation.

5.3. The matter in the disk

The fact that the average rate of matter accumulation in the disk, derived from the observations (total outburst energy) and the mass flow rate towards the black hole (derived from ADAF spectral fitting) are just about the same seems surprising, as pointed out by Tanaka (1999). Menou et al.(1999b) estimated the relative importance of both rates and came to the conclusion that those are about equal (see also Menou et al. 1999a). Our computations naturally provide a value $\langle\dot M_{\rm acc}\rangle/\dot M_T \approx$ 0.35-0.55 for outburst recurrence times of 30 to 50 years, characteristic for SXTs.

5.4. The cause of the mass transfer

Assuming an evolved companion star the mass transfer rates caused by magnetic braking might be low enough to lead to outbursts. These rates of mass overflow from the secondary star according to the suggestions by Verbunt & Zwaan (1981) and Mestel & Spruit (1987) depend only weakly on the primary mass.

The observed outbursts strongly point to the fact that the transfer rates are marginal to trigger an outburst. Then one would conclude that the rates have a spread such that no outbursts or only rare outbursts occur. But such an interpretation is not possible if the limiting rate is so different for different black hole mass, assuming that the observed systems do not all have the same black hole mass (for a discussion see Bailyn et al. 1998). Only if the transfer rates depend somehow on the primary mass could these rates be such that marginally triggered rare outbursts occur for different black hole masses. We do not know about any mechanism which could cause these transfer rates.

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