EVOLUTION OF THE ACCRETION DISK IN BLACK HOLE X-RAY TRANSIENTS

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Abstract Several black hole X-ray transients have a very long recurrence time, decades of years. We study the evolution of the disk during quiescence and interpret the outburst behaviour as a marginal occurrence of a dwarf nova type disk instability in the cool outer accretion disk. We determine the amount of mass stored in the disk until the triggering of the outburst and the recurrence time. The evaporation of matter from the inner accretion disk to a coronal flow is an essential feature of the disk evolution and depends on the black hole mass. For accretion rates slightly lower than those in the known black hole X-ray transients the disk would be stationary, the systems would persistently remain in a cool state.

1. INTRODUCTION

Since three decades now satellites allow to observe objects in X-rays. The catalogue of van Paradijs (1995) contains information on about 200 X-ray binaries. These sources are semi-detached binary stars in which matter is transferred from a more or less normal star to a neutron star or a black hole. The radiation in X-rays is due to accretion and accretion disks around compact objects became a subject of intense studies. The similarity of the accretion processes in both stellar disks and disks around supermassive black holes allows applications to Active Galactic Nuclei.

We distinguish two classes of objects: high-mass and low-mass X-ray binaries (HMXBs and LMXBs) depending on the mass of the secondary star. The HMXBs are systems with an O or B star companion with a stellar wind zone around. Mass flow rates are high. About one third of the X-ray binaries are not persistently visible and are detected as transient sources only. Transients alternate between outbursts with increase of the X-ray flux by more than two orders of magnitude within several days and low luminosity phases (quiescence) where they might not be detectable. During the outburst the spectra are soft, as also observed for the luminous persistent LMXBs. Therefore these binaries are called "soft X-ray binaries" or "X-ray novae". Simultaneous to the X-ray outbursts optical outbursts occur. Properties of X-ray novae are summarized in the review of Tanaka & Shibazaki (1996). Due to the remarkable increase of sensitivity obtained with focussing X-ray telescopes detailed studies of the quiescent state became possible (Asai et al. 1998). Chen et al. (1997) carried out a statistical study of all X-ray and optical lightcurves of SXTs, neutron star and black hole systems.

The aim of our investigation is the understanding of SXT outbursts as a result of a thermal-viscous disk instability similar to the situation in dwarf novae. We limit our work to the evolution of accretion disks around black holes. If the primary is a neutron star the irradiation of the disk by the bright neutron star surface has to be taken into account. Already a decade ago Huang & Wheeler (1989) and Mineshige & Wheeler (1989) argued that a disk instability like in the dwarf nova systems, where the primary star is a white dwarf, causes the rare outbursts of black hole transients. Several aspects of the physics of accretion disks in SXTs were examined by Cannizzo (1998).

The outburst recurrence times are very long for several SXTs, for some only one outburst was recorded. For dwarf novae such long recurrence times are rare, then usually the outburst amplitude is very high. These systems are known as "tremendous outburst amplitude dwarf novae", TOADs (Howell et al. 1995). The best observed system, WZ Sagittae, with outbursts every 31 years seems similar to the transients. The amount of matter accumulated in the disk for the outburst is about 1-2 10^{24}g (Smak 1993), and is only a factor of about 3 larger for the transient source A0620-00 (McClintock et al. 1983). Despite the similarity of WZ Sge stars and SXTs (Kuulkers 1999) there is one important difference between disks in WZ Sge stars and SXTs: the size of the disk in WZ Sge with the orbital period of only 81.6 minutes is much smaller than those in SXTs with typical periods of several days. The viscosity parameter in WZ Sge star disks therefore has to be a factor of 10 to 100 lower than in SXT disks if the same amount of matter should be accommodated in the much smaller disk (Meyer-Hofmeister et al. 1998). In WZ Sge stars as well as in SXTs the outbursts probably are only marginally triggered, as will be shown later for SXTs.

The spectra of quiescent black hole SXTs are not consistent with a standard thin disk reaching inward to the black hole, as pointed out by McClintock et al. (1995) and Narayan et al. (1996). But the spectra can be modelled with accretion via an ADAF (for a review see Narayan et al. 1999). From basic accretion disk theory also follows that the thin disk cannot reach inward to the vicinity of the compact star in the cool state. The inner disk would be hot even for very low mass flow rates. Such a disk with a hot inner part and a cool outer part could not be in a stationary state, it would rather undergo changes

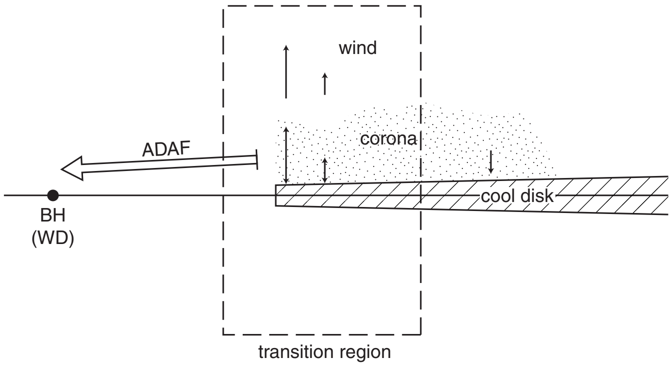

Figure 1.1 Schematic drawing of cool disk, corona and ADAF

between hot and cool state on short timescales (Meyer 1984). Instead at a certain distance from the black hole the thin disk ends due to evaporation and the accretion continues in the form of a coronal flow/ADAF. This transition is an essential feature of disk evolution.

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 diffusion process. Conservation of mass and angular momentum give the diffusion equation (see e.g. Frank et al. 1992). Matter flows inward and angular momentum is transported outward in the disk. We consider a geometrically thin disk with a corona above. 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 have to be considered in the thin disk and the corona together. The appropriate diffusion equation for the change of surface density in the cool disk then includes an additional term for the mass evaporation. The inner edge of the thin disk is determined by the balance between mass flow in the disk and evaporation. Further in matter only flows via the corona towards the compact object. The outer edge of the thin disk is determined by the conservation of angular momentum. In the corona matter mainly flows inward, but a small amount flows outward for conservation of angular momentum. The diffusion equation for the cool disk combined with a corona 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). The situation is similar for disks around black holes. The disk evolution was studied in detail modelling A0620-00 (Meyer-Hofmeister & Meyer 1999).

We compute the disk evolution. The main features are the following. After an outburst the surface density distribution in the cool disk is assumed to be low and the thin disk is in the cool state. During quiescence a part of the matter transferred from the companion star accumulates in the cool disk, another part flows inward and is evaporated in the disk region near the inner edge. No thin disk exists further inward, only the hot coronal flow (see schematic drawing Fig. 1). During the formation of the coronal flow wind loss occurs, so that only about 80% of this matter can yield the mass supply for the advection-dominated accretion flow 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 value chosen for the disk viscosity parameter.

To simulate the situation in SXTs we follow the evolution of the cool accretion disk in combination with the hot corona for different primary star masses and mass overflow rates. To solve the diffusion equation the viscosity-surface density relation and the parameterized viscosity have to be given. We use values as usually taken for dwarf nova disk modelling, the viscosity-surface density relation from Ludwig et al. (1994) and the viscosity parameter (Shakura &

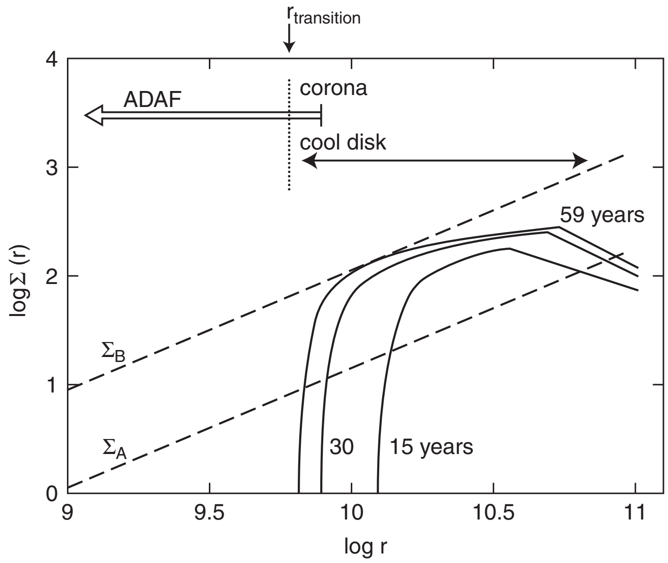

Figure 1.2 Disk evolution of A0620-00, ”standard case”, accumulation of matter in quiescence. $\Sigma_{\rm A}$ and $\Sigma_{\rm B}$ critical surface densities. For the surface densities between these values two states, hot and cold, are possible. When accumulation of matter reaches $\Sigma_{\rm B}$ an outburst sets in.

Sunyaev 1973) $\alpha_{\rm cool}$=0.05 for the cool state. Evaporation we take into account using a scaling law derived for the rate $\dot{M}_{\rm ev}$ as function of primary mass M_1 and distance r to the primary (Liu et al. 1995).

3. RESULTS FOR A0620-00

As a pilot study for disk evolution in SXTs we modelled the often observed source A0620-00 (Meyer-Hofmeister & Meyer 1999). Constraints from the observations are the amount of matter stored in the disk and the recurrence time. For our "standard case" evolution we took the following parameters: primary mass M_1=$4M_\odot$, mass overflow rate $1.9\,10^{-10}M_\odot/\rm{yr}$. In our modelling we get the onset of the outburst after slightly less than 60 years as observed. The computed amount of matter stored in the disk agrees with the amount of matter deduced from the observed outburst lightcurve. It is not trivial to meet these two constraints together. Further we find very good agreement with the mass accretion rate in the inner disk and the transition radius derived from the fitting of SXT spectra in low state, based on the ADAF concept by Narayan et al. (1997).

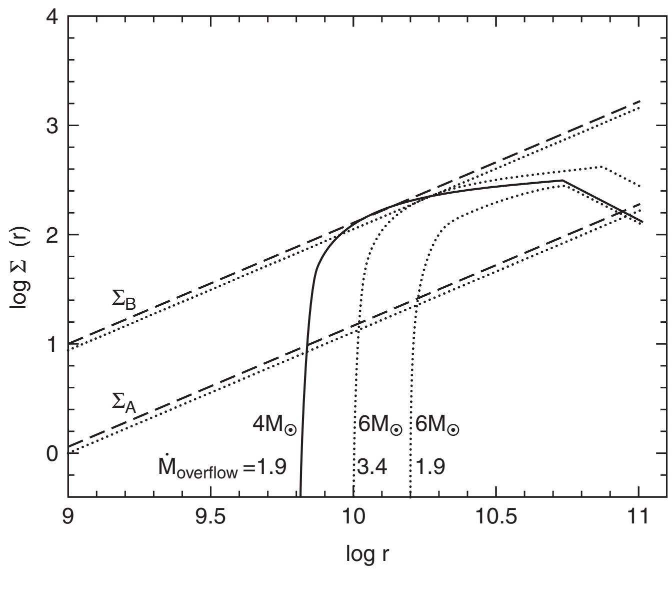

Figure 1.3 Comparison of accumulation of matter during quiescence for black holes of 4 and $6M_\odot$,(mass overflow rates in $10^{-10}M_\odot/\rm{yr}$). Solid line surface density distribution at the onset of outburst for $4M_\odot$ (same as in Fig. 2), dotted line onset of outburst for $6M_\odot$: due to more efficient evaporation the hole is larger and a higher mass overflow rate, $3.4\,10^{-10}M_\odot/\rm{yr}$ instead of $1.9\,10^{-10}M_\odot/\rm{yr}$, is needed to produce an outburst (in our example after 55 years). The low rate of $1.9\,10^{-10}M_\odot/\rm{yr}$ would lead to a stationary disk without an outburst.

In Fig. 2 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 total amount of matter stored at the onset of the outburst was 6.9 10^{24}g.

The results for A0620-00 already indicate the main features of disk evolution which we study in our more general investigation of X-ray transients. It is interesting how the black hole mass affects the disk evolution. We also computed the evolution for a disk around a 6 $M_{\odot}$ black hole. The evaporation rate is higher than in the case of 4 $M_{\odot}$, the transition radius is larger. A higher mass overflow rate is necessary to compensate for this. For 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. 3 we show the distribution of surface density at the onset of the outburst for 4 and 6 $M_{\odot}$. The critical surface densities are slightly different for the two primary masses. The rate that is 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.

4. RESULTS FOR TRANSIENT SOURCES WITH A BLACK HOLE MASS OF 4 TO 12 $M_{\odot}$

Based on our modelling of the accretion disk evolution of A0620-00 we computed the evolution for a variety of parameter values to study the properties of transient systems in general (for details see Meyer-Hofmeister & Meyer 2000). The results are recurrence time and amount of matter accumulated in the disk during the quiescence.

In Fig. 4 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. The higher evaporation efficiency for higher primary mass leads to the formation of a more extended inner disk hole and accumulation of matter in further outward geometrically larger disk regions. To reach the critical surface density for the disk instability definitely requires the accumulation of more matter. This means higher mass overflow rates are necessary to trigger an outburst within the same recurrence time, as can be seen from Fig. 4.

For the majority of X-ray novae the observed recurrence time is very long, $\geq$ 50 years (Tanaka & Shibazaki 1996). The question arises why we observe predominantly these systems and not also a larger number of systems with recurrence times around 10 years. The outburst behaviour is determined by the mass overflow from the companion star. But "magnetic braking" (Verbunt & Zwaan 1981, Mestel & Spruit 1987) thought to be the cause for the loss

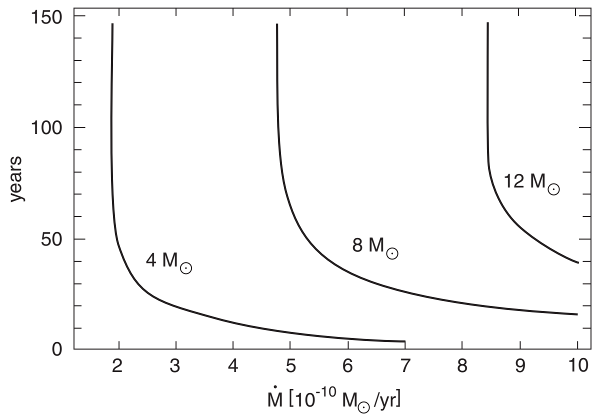

Figure 1.4 Computed recurrence times of outburst for different black hole masses and orbital periods of the binary as a function of the mass overflow rate $\dot{M}$. Note that the recurrence time increases steeply with $\dot{M}$ if the situation of only marginal triggering of the disk instability is approached. For even lower rates the disk is stable.

of angular momentum from the binary and for the mass transfer, is not well understood for the black hole binaries (for a discussion of the secular evolution see King et al. 1997).

The second interesting result is the amount of matter accumulated in the disk until the next outburst is triggered. In Fig. 5 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 the narrow range shown in Fig. 5, for a wide variation of the recurrence time. The observed outburst lightcurves allow to estimate the amount of matter accreted during the outburst. If we compare with the available data our results lie in that range.

Our computations also give what fraction of the matter tranferred from the companion star is actually accumulated in the disk. For an orbital period of 8 hours we show in Fig. 6 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). Since the amount of accumulated matter is always about the same for long recurrence times, $\geq$ 10 years, 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.

4.1 STATIONARY SYSTEMS

Our results for disk evolution (Fig. 4) show that, especially in the case of long recurrence time, small changes in the mass overflow rate from the companion star essentially affect the outburst recurrence time. There might exist low-mass X-ray binaries which we do not detect since they are in the low state for a long time. The detection probability is very low; only if the position of a transient system is known from an earlier outburst the source can be observed in quiescence (for a discussion of the observational signatures of faint X-ray binaries see Menou et al. 1999). For rates only slightly less than the rate which provides the onset of instability (for example after 59 years in A0620-00) the critical surface density can not be reached, the system is globally stable. Probably, as also suggested by Menou et al. (1999), many such systems, faint persistent soft X-ray binaries, exist.

5. SUMMARY

The investigation of disk evolution in soft X-ray transients gives insight to the nature of these systems. The large range of observed recurrence times can be understood as resulting from a dwarf nova type instability in the cool accretion

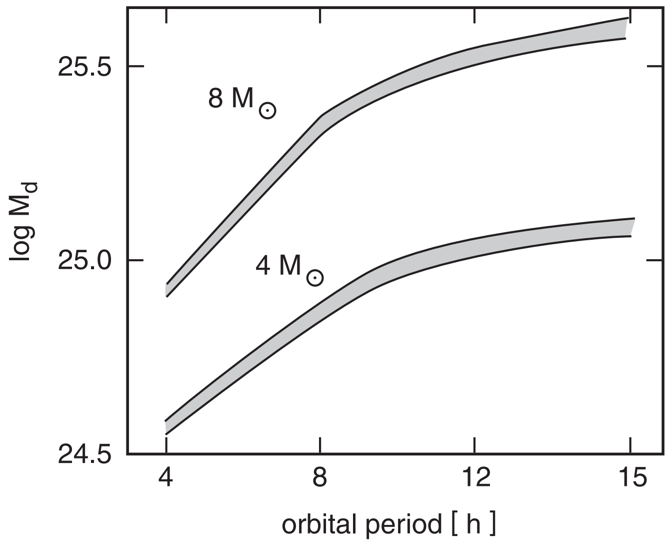

Figure 1.5 Amount of matter accumulated in the accretion disk. The amount differs with the mass tranfer rate. We show a lower value, which belongs to a marginally stable disk (for a stable disk all matter flows through changing to a coronal flow at the inner edheof the cool disks) and an upper value which is the maximum value of matter found for the evolution with transfer rates belonging to recurrence times $\geq$ 10 years.

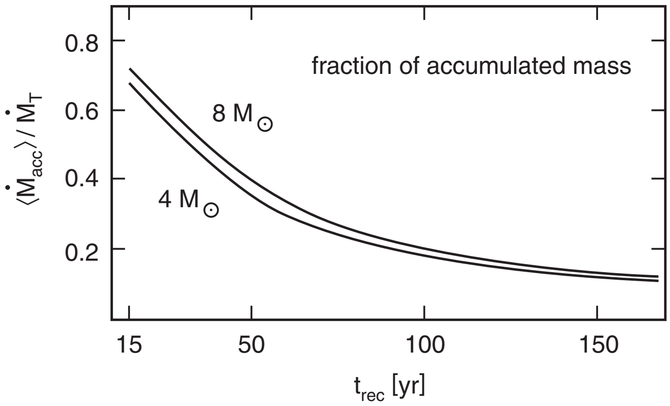

Figure 1.6 Fraction of accumulated matter (average over recurrence time) to matter transferred from the companion star $<\dot{M}_{acc}>/\dot{M}_T$ as a function of the recurrence time.

disk with mass overflow rates from the companion star of order of several $10^{-10} M_\odot/\mathrm{yr}$. About half of this matter from the companion star accumulates in the disk for the next outburst, the other half accretes onto the black hole via a coronal flow/ADAF. This is in good agreement with what is found from the observations for accretion during quiescence (Tanaka 1999).

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