Mechanisms for the outbursts of soft X–ray transients

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Abstract. We show that the Keplerian thin disk in quiescent Soft X-ray Transients cannot extend down to the last stable orbit around the central black hole. We analyse the properties of the Narayan, McClintock & Yi (1996) model of quiescent Soft X-ray Transients in which the cold Keplerian disk has its inner edge at a large transition radius and transforms to a hot, advection-dominated flow on the inside. We show that outbursts of transient sources could be triggered in this model either by a pure thermal accretion disk instability or by a disk instability generated by an enhanced mass transfer from the stellar companion. Both mechanisms operate in the outer thin disk and could be at work, either in different systems or in the same system at different epochs, depending on the mass transfer rate and the value of the viscosity parameter $\alpha_t$ of the thin disk. We show that the recurrence time between outbursts in SXTs can be explained with values of $\alpha_t$ similar to these required by the dwarf nova disk instability model instead of the unreasonable low values needed in the model in which the thin disks extends down to the last stable orbit. We extend the Narayan, McClintock & Yi (1996) model to the case when the outer disk is non-stationary. We show that such disk is too cold to account for the observed UV flux. This difficulty is common to all models in which the outer disk is assumed to be optically thick.

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

1. Introduction

Soft X-ray Transients (SXTs) are close binary systems which undergo large amplitude outbursts with a recurrence time of about 1 – 50 years (see e.g. White 1994 for a review). In most cases SXTs disappear from the X-ray sky between outbursts leaving only the companion star observable as a dim optical source. Most SXTs are low mass X-ray binaries (LMXBs), that is, binary systems in which a neutron star or a black hole accretes matter lost by a Roche-lobe filling low-mass stellar companion. A minority of SXTs show X-ray bursts during decline from outburst (e.g. Koyama et al. 1981) and must contain neutron stars. In several other SXTs, observations of the companion have allowed measurement of a mass function which is larger than the maximum mass of a neutron star (Orosz et al. 1994; Casares & Charles 1994; Orosz et al. 1995; Casares, Charles & Marsh 1995; Bailyn et al. 1995). These are certain to be black holes. For the remaining SXTs there is no direct evidence on whether they have neutron stars or black holes, but it is believed that the majority of them contain accreting black holes (see Tanaka & Lewin 1995 and van Paradijs & McClintock 1995).

Most of the outburst energy in an SXT is emitted in rather soft (1 to few keV) X-rays. It has been claimed that the spectra of black–hole SXTs (BSXTs) are characterised in outburst by an ‘ultra–soft’ (White et al. 1984) component, and that this is not seen in neutron star SXTs. However, in a few cases involving good black hole candidates (e.g. V404 Cyg) such a component has not been observed (Harmon et al. 1994). At least one black hole SXT was observed to emit very high energy photons, namely Nova Muscae 1991 which had an $e^+–e^-$ annihilation line (Goldwurm et al. 1993). On the other hand some neutron star SXTs have also been observed to emit above 100 keV (Barret et al. 1993). It is therefore not clear if there are any spectral characteristics that would allow, in general, to distinguish between neutron star and black hole transients.

The binary periods of SXTs generally lie in the range between 5 hours and 6 days. (The ‘ultra-soft’ transient system 4U 1630-47, [Parmar, Angelini & White 1995] could be an exception if its period is confirmed to be 601.7±3.0 days.) SXTs are therefore LMXBs with main–sequence dwarf companions or, at longer periods, (sub)giant com-
companions (King 1993). As in the case of their close cousins, the dwarf novae, which have central white dwarfs instead of neutron stars or black holes, two kinds of models have been proposed to explain the outbursts of SXTs.

Hameury, King & Lasota (1986) proposed a model in which outbursts are due entirely to a mass transfer instability in the X-ray illuminated regions of the mass-losing companion. It was shown, however, by Gontikakis & Hameury (1993) that the existence of SXTs with orbital periods under ~ 10 h is a problem since the model is unable to produce the observed short (∼ 10^6 s) timescales (see also Lasota 1995).

The dwarf nova disk instability model (DIM) (see e.g. Cannizzo 1993) has been extended to the case of BSXTs by Huang & Wheeler (1989) and Mineshige & Wheeler (1989). Below we discuss problems and difficulties that this model encounters when confronted with observations.

In addition to the above two proposals, one should also consider models in which the two mechanisms are at work in the same source. For example, the disk instability could be triggered by an enhanced mass transfer (EMT). Such “mixed” or “hybrid” models have been proposed for the superoutbursts of SU UMa type dwarf novae (Duschl & Livio 1989; Smak 1995,1996; Lasota, Hameury & Huré 1995) and suggested as a possible explanation of SXT outbursts (Lasota 1996).

In this paper we analyse how various versions of the disk instability model could be applied to outbursts of BSXTs. In section 2 we discuss the difficulties of the dwarf nova DIM when it is applied to BSXTs. Section 3 gives a short review of the advection-dominated flow model of quiescent BSXTs (Narayan, McClintock & Yi 1996). In section 4.1 we show that the ‘hybrid’ EMT-triggered DIM could apply to BSXTs. In section 4.2 we show that the outer cold disk in BSXTs could be globally unstable and so BSXT outbursts could be triggered by a thermal disk instability, as proposed independently by Mineshige (1995). We discuss problems and difficulties in section 5 and present conclusions in section 6.

2. The dwarf–nova type disk instability model for SXTs outbursts

The DIM is based on the fact that accretion disk equilibria are unstable at effective temperatures in the range 5000 – 10000 K, depending on the radial distance from the center.

It is conventional to discuss the instability in the Σ – T_{eff} plane, where Σ is the surface density of the disk and T_{eff} is the effective temperature. At a given radius, disk equilibria trace a characteristic ‘S’ shaped curve on this plane, as indicated by the example shown in Figure 1 (based on [Hameury, Huré & Lasota 1995]). The middle branch of the S (shown by a dotted line) represents thermally and viscously unstable equilibria and cannot represent physically accessible states. Therefore, locally, an accretion flow has to choose between the two stable branches of the S (solid lines), either the upper ‘hot’ branch or the lower ‘cold’ branch. The upper branch exists only above a minimum surface density Σ_{min} and minimum mass accretion rate ˙M_{min}ǔ T^4_{eff}, where the value of T_{eff} corresponds to Σ_{min}, while the lower branch exists only below a certain Σ_{max} and ˙M_{max}. Note that the limiting surface densities and accretion rates vary with the radius R.

If the steady mass transfer rate ˙M_{T} supplied by the secondary star corresponds to conditions in the unstable middle branch, i.e. if ˙M_{max} < ˙M_{T} < ˙M_{min}, then the disk cannot maintain a steady state configuration and is forced into a local ‘limit cycle’ behaviour, alternating between the cold and hot branches. A dwarf nova outburst or SXT outburst would then correspond to the transition from the cold to the hot state. Observations indicate that dwarf nova and SXT outbursts are global events where the entire disk makes the transition. In order to produce such a global outburst, it is required that the pre-outburst quiescent disk be entirely on the lower branch at all radii R, i.e. we must have Σ(R) < Σ_{max}(R) at all R.

In general, the critical density of the cold branch can be represented as (Smak 1993):

\[ Σ_{max} = Σ_0 R^{b_R} M^{-b_R/3} α_t^{b_α}, \]  

where M is the mass of the central object, α_t is the Shakura-Sunyaev viscosity parameter of the thin disk, and the index b_R ≈ 1 so that Σ_{max} is an increasing function of R. The α exponent is usually negative, b_α ≤ 0.

In a disk around a black hole in a binary system the radius may vary by 5 to 6 orders of magnitude so that Eq. (1) would imply very low densities in the quiescent inner

Fig. 1. Equilibrium solutions for a Keplerian accretion disk at R = 10^{10} cm, for M = 10M_{⊙} central mass and α_t = 0.01. The dotted part of the S-curve is thermally and viscously unstable.
disk. For example, introducing numerical values in Eq. (1) according to the formula given by Smak (1993), we obtain

$$\Sigma_{\text{max}} = 0.03 \, r^{-1.11} m_{10}^{0.74} \left( \frac{\alpha_t}{0.01} \right)^{-0.79} \text{ g cm}^{-2},$$  (2)

where $r = R/R_S$ is the scaled radius in units of the Schwarzschild radius $R_S = 2GM/c^2$, and the mass is scaled according to $m_{10} = M/10M_\odot$.

According to the DIM, the quiescent disk in a dwarf nova or SXT system is not in global equilibrium. Instead, the local accretion rate increases with distance from the center (see Eq. (5) and the effective temperature is constant with radius (see Eq. (1)). This last property is confirmed by observations (e.g. Wood et al. 1986; 1989). Assuming that outbursts begin near the inner disk edge and taking $T_{\text{eff}} = \text{constant}$, Smak (1993) obtains for the recurrence time

$$t_{\text{rec}} \approx t_{\text{vis}} = \frac{2R_S^2}{3\nu},$$  (3)

where $R_{in}$ is the radius of the inner edge of the disk and $\nu$ is the kinematic viscosity coefficient. In most BSXTs the recurrence time is longer than $\sim 10$ yr. Therefore, we obtain from Eq. (3) a condition on the viscosity coefficient:

$$\nu \lesssim 276 \, t_{\text{rec}}^{-1} R_{in}^{-2} m_{10}^{-2} \text{ cm}^2 \text{ s}^{-1},$$  (4)

where $t_{\text{rec}}$ is the recurrence time in units of $10^9$ s. Combining Eq. (3) and Eq. (4), we then obtain the following inequality which has to be satisfied by the accretion rate at the inner edge of a quiescent disk if the DIM is correct (Lasota 1995):

$$\dot{M}_{\text{in}} \lesssim 3 \pi \nu \Sigma_{\text{max}} \approx 83.5 \, t_{\text{rec}}^{-1} R_{in}^{-2} m_{10}^{-2} \left( \frac{\alpha_t}{0.01} \right)^{-0.79} \text{ g s}^{-1}.$$  (5)

The DIM of Mineshige & Wheeler (1989; MW) satisfies this inequality.

Eq. (5) provides an observational test of the DIM. Several BSXTs have been observed by GINGA (Mineshige et al. 1992) and ROSAT (see Verbunt 1995), and two systems, A0620-00 and V404 Cyg, have been detected at levels corresponding to accretion rates (assuming an efficiency of 0.1, see below) of at least $\sim 1.3 \times 10^{11}$ g s$^{-1}$ for A0620-00 and $3 \times 10^{12}$ g s$^{-1}$ for V404 Cyg (Mineshige et al. 1992; McClintock, Horne & Remillard 1995; Verbunt 1995). For reasonable values of $\alpha_t \sim 10^{-2}$, these accretion rates are several orders of magnitude larger than the values implied by Eq. (5) for $r_{in} = 3$ (inner edge at the last stable orbit as in the dwarf–nova type model). Therefore, the detections of X-ray radiation from quiescent SXTs contradict the disk instability model, at least in the version proposed by MW (Mineshige et al. 1992).

We note that in the case of A0620–00, the prototypical BSXT, the optical luminosity suggests a mass accretion rate of $\sim 6 \times 10^{15}$ g s$^{-1}$ in the outer part of the accretion disc (McClintock et al. 1995), at $r > 10^4$.

3. Advection-dominated flows in quiescent SXTs

The observation of X-ray emission in quiescent SXTs at low luminosities poses an insurmountable obstacle to models in which the accretion disk is of the Shakura–Sunyaev type with $r_{in} = 3$. On the one hand, the requirement of Eq. (5) can be reconciled with the deduced mass accretion rate of $\dot{M}_{\text{in}} \sim 10^{11} - 10^{12}$ g s$^{-1}$ only if we assume a very low viscosity in the inner disk, e.g. $\alpha \sim 10^{-12}$ which is almost equivalent to having no viscosity at all. Here we have assumed $\alpha = \text{const.}$ According to the DIM (see e.g. Cannizzo et al. 1995) $\alpha$ should be of the form $\alpha_0 (H/R)^n$, where $H$ is the disk semi-thickness. Cannizzo et al. (1995) find $\alpha_0 = 50$, $n = 1.5$ and the values of $\alpha$ they obtain are well in excess of those required by Eq. (5) confirming the failure of the DIM to account for the observed properties of quiescent SXTs. On the other hand, the X-rays have to be produced by a process connected to viscosity, and if we assume a standard thin disk with $\dot{M}_{\text{in}} \sim 10^{11}$ g s$^{-1}$ as implied by the X-ray observations, the effective temperature will be so low that the disk will radiate hardly any X-rays at all. In other words, the required value of $\alpha$ in the dwarf–nova type model is unreasonable, and even if we ignore this problem, it is impossible to fit both the low luminosity and the temperature of the radiation simultaneously. The advection-dominated model of Narayan, McClintock & Yi (1996) (hereafter NMY) presents a solution to this problem.

The fundamental property of advection-dominated accretion flows (ADAFs) is that the efficiency with which energy is radiated is very low, so that most of the heat released by viscous friction (or other processes) is advected into the central black hole and only an almost infinitesimal amount is radiated away. Models of ADAFs were first constructed for optically thick flows with angular momentum (Begelman 1979; Begelman & Meier 1982; Abramowicz et al. 1986, 1988). The models correspond to very high (super-Eddington) accretion rates and have not yet found an application to real astrophysical objects.

As pointed out by Narayan and Popham (1993), advection may play an important role also in the case of optically thin flows which are notoriously non-efficient radiators. In this case, the viscously heated gas flows into the black hole on a shorter timescale than its cooling time and therefore a large fraction of the energy is advected rather than radiated. Models of optically thin advection-dominated flows were constructed in a series of papers by Narayan & Yi (1994, 1995a,b) and Abramowicz et al (1995), Chen (1995) and Chen et al. (1995).

The Narayan & Yi (1995b) version of the ADAF model deals with a two-temperature plasma which is ra-
diately cooled by bremsstrahlung, synchrotron emission and Comptonization. This model was first successfully applied to the Galactic Center source Sgr A* (Narayan, Yi & Mahadevan 1995), and soon after applied to quiescent SXTs (NMY). Recently the Narayan & Yi (1995b) model was applied to the dwarf active galactic nucleus NGC 4258 (Lasota et al. 1996).

The accretion flow in the NMY model consists of two parts: outside some radius $r_t$, the accreting gas takes the form of a standard, cold, geometrically thin, Keplerian disk. However, inside $r_t$, the accretion proceeds in the form of an ADAF. Here, the gas becomes extremely hot, with the ions reaching temperatures $\sim 10^{12}$ K and the electrons going up to $T_e \sim 10^{9.5} - 10^{10}$ K. The very high ion temperature causes the gas to be very thick in the vertical direction; indeed, the flow is essentially quasi-spherical rather than disk-like, though it is still partially supported by rotation. For simplicity, NMY assumed that the accretion rate is constant throughout the whole flow.

In the NMY model, the optical and UV radiation is produced by the outer thin disk, while the inner advection-dominated flow, because of its very high temperature, produces all the hard radiation in X-rays and soft $\gamma$-rays. Even though the same $\dot{M}$ flows through the outer and inner zones, the model quite naturally explains the low luminosity of the X-rays as a consequence of the extremely low radiative efficiency of the ADAF. The viscous energy dissipation in the ADAF is significantly larger than that in the outer thin disk since most of the gravitational potential energy is released in the ADAF. However, virtually all of this energy is advected into the black hole and only a very tiny fraction is radiated. This effect is so strong that the luminosity of the ADAF is actually less than that of the outer disk.

NMY used their model to fit the spectra of three quiescent BSXTs: A6020-00, V 404 Cyg and X-ray Nova Muscae 1991. The fits to the observed optical–UV to X-ray spectra of the three SXTs are very good. The models depend basically on two parameters, $\dot{M}/\alpha$ (where $\alpha$ refers to the viscosity parameter in the ADAF and is distinct from $\alpha_t$ of the outer thin disk) and $r_t$. The other parameters are either given directly by observations (for example the black hole mass) or the fits turn out to be insensitive to their values (for example the ratio of the gas to the total pressure).

4. The outburst mechanism

The presence of an inner hot advection-dominated flow removes the contradiction between the observed X-ray emission and the properties of a Shakura-Sunyaev type disk. There remains the question of why BSXTs go into outbursts.

Could the mechanism be related to the hot inner flow? Abramowicz et al (1995) and Narayan & Yi (1995b) showed that there is a maximum accretion rate above which there are no optically thin advection-dominated solutions. In the Narayan & Yi model the critical accretion rate is $\dot{M} \sim 0.3\alpha^2\dot{M}_{Edd}$ for $R < 10^3 R_S$ and $\dot{M} \sim 0.3\alpha^2\dot{M}_{Edd}(R/10^3 R_S)^{-1/2}$ for $R > 10^3 R_S$.

Figure 2, taken from Narayan (1995) and based on Chen et al. (1995), represents the structure of all possible accretion solutions for the case of a 10 $M_\odot$ black hole. Label 1 refers to a region where the only allowed solution is an advection-dominated one, label 2 refers to a radiatively-cooled zone, and label 3 corresponds to a region where both types of solutions are allowed. In region 4 there are no stable solutions at all. One could speculate that if the accretion rate at which matter is brought to the hot ADAF corresponded to region 4, the system would be forced into a thermal runaway and a limit cycle (see e.g. Chen et al. 1995). There is, however, a problem with this scenario. NMY found that they needed $\alpha \sim 0.1 - 0.3$ in the advection-dominated inner zone of their models. For such $\alpha$, zone 4 exists only for mass accretion rates above $\sim 10^{-2}\dot{M}_{Edd}$. But the mass transfer rates in quiescent SXTs estimated by NMY correspond to $\dot{M} \approx (10^{-3} - 10^{-4})\dot{M}_{Edd}$. For such low accretion rates an ADAF solution is always present. Furthermore, ADAFs are thermally stable by construction (Abramowicz et al. 1995, Narayan & Yi 1995b, Kato et al. 1995) The hot inner flows in quiescent SXTs are therefore stable and we cannot expect to find there the cause of outbursts.

Thus the outburst mechanism in SXTs must be associated with the outer cold disk which could be, or become thermally unstable. Below we will investigate the mechanisms that could cause an outburst in the outer thin disk.
4.1. Disk instability triggered by enhanced mass transfer

In this and the next sections we will study the stability properties of the outer ‘standard’ thin disk, which extends from the transition radius \( r = r_{\text{tr}} \) to the outer radius \( r = r_{\text{out}} \). As explained in Section 2, for the disk to be globally unstable, the mass transfer rate \( \dot{M}_T \) must satisfy at some radius the inequality

\[
\dot{M}_{\text{max}} < \dot{M}_T < \dot{M}_{\text{min}}
\]

(6)

where \( \dot{M}_{\text{max}} \) and \( \dot{M}_{\text{min}} \) are defined in Section 2. The range of unstable mass transfer rates depends on the size of the disk. As an example Figure 3 shows surface density profiles of equilibrium accretion disks around a 10M\(_{\odot}\) black hole, where the disk has been truncated at \( r = r_{\text{tr}} \) in accordance with the NMY model. The accretion rate \( \dot{M} \) is constant for each curve. The unstable part of the curve is represented by a dotted line, the cold stable configurations correspond to the solid line. Models by Hameury et al. (1995) were used in this calculation with a thin disk viscosity parameter \( \alpha_t = 0.01 \). Note that this is smaller than the value \( \alpha \sim 0.1 - 0.3 \) which NMY found was necessary for a consistent model of the advection-dominated region. There is no contradiction in this since there is no reason for \( \alpha \) to be the same in the advection-dominated and standard regions; one should rather expect \( \alpha \) to be lower in the outer thin disk compared to the inner hot flow.

![Figure 3](image)

**Fig. 3.** The surface density profiles of equilibrium accretion disks around a black hole of 10M\(_{\odot}\) with \( \alpha = 0.01 \). Cold, stable equilibria are represented by solid lines, the unstable equilibria correspond to the dotted lines. Inner regions of thin disks could be truncated at radii \( \sim 10^{3-4} \) Schwarzschild radii \( (R_s) \) (NMY).

A globally stable, cold accretion disk cannot be represented by a curve that crosses the \( \Sigma = \Sigma_{\text{max}} \) line. Assuming \( \Sigma < \Sigma_{\text{max}} \) at \( r = r_{\text{out}} \), we can have a situation where with decreasing \( r \), we reach the condition \( \Sigma = \Sigma_{\text{max}} \) at some radius \( r = r_{\text{crit}} \). The disk can be in cold equilibrium only for \( r_{\text{crit}} < r < r_{\text{out}} \). Continuing to \( r < r_{\text{crit}} \), the segment of the curve between \( \Sigma_{\text{max}} \) and \( \Sigma_{\text{min}} \) is unstable while the curve to the left of \( \Sigma_{\text{min}} \) represents hot equilibria.

For each mass transfer rate \( \dot{M}_T \), there exists therefore a critical radius \( r_{\text{crit}} \) outside of which the disk is globally stable in the cold state. From Figure 3 we can see that the global state of the disk will depend on the exact value of \( r_{\text{tr}} \) relative to \( r_{\text{crit}} \). For example, for \( \dot{M} = 10^{15} \text{ g s}^{-1} \), if the outer disk is truncated at \( r_{\text{tr}} = 10^4 \) we have a globally stable disk whereas if \( r_{\text{tr}} = 10^3 \) the disk is globally unstable. For the moment we consider \( r_{\text{tr}} \) to be a free parameter that is fixed by best ‘fit’ to the spectrum of the quiescent SXT in combination with other parameters such as the black hole mass, \( \alpha \) etc. (see NMY). Physically, of course, the value of \( r_{\text{tr}} \) should be determined by the process that leads to the formation of the ADAF, such as coronal evaporation (see e.g. Meyer & Meyer–Hofmeister 1994) or heating by diffusive energy transport (Honma 1995). The theories of these processes have not yet developed to the point where they can make robust predictions of \( r_{\text{tr}} \).

Lasota et al. (1995) studied a similar problem in the context of dwarf nova outbursts. Some SU UMa–type dwarf novae show only very rare and very long superoutbursts and no (or almost no) ‘normal’ outbursts. The best known system in this class is WZ Sge. Such DN systems are the closest relatives of BSXTs. The DIM applied to dwarf novae requires some modifications before it can be applied to the whole class of observed events. In particular, the so–called UV–delay problem and the X–ray and UV emissions from quiescent DNs require a ‘hole’ in the inner disk regions (see e.g. Meyer & Meyer–Hofmeister 1994). This ‘hole’ can be produced by magnetic disruption if the white dwarf is (weakly) magnetized (Livio & Pringle 1992) or it can be the result of evaporation (Meyer & Meyer–Hofmeister 1994).

Lasota et al. (1995) show that if the inner regions of accretion disks in quiescent dwarf nova systems are removed, the remaining disk is globally stable for mass transfer rates \( \lesssim 10^{15} \text{ g s}^{-1} \). This implies that (super)outbursts in such systems have to be triggered by an enhanced mass transfer from the companion. They suggest that the lack of normal outbursts in WZ Sge results because of its low mass transfer rate: there are no outbursts because the disk is stable. A superoutburst would be triggered by an EMT which would put the disk into a globally unstable state; in other words, superoutbursts would be due to a disk instability generated by an increased mass transfer. Observations show that the mass transfer increases prior to and during the superoutburst so that such a hybrid mechanism could be at work in SU UMa’s (Smak 1995, 1996). The alternative model (see Osaki 1996 for a review) in which
superoutbursts are due to a pure disk instability, the so-called tidal-thermal instability, is yet to be confirmed by the observational properties of SU UMa (Smak 1991) and requires the viscosity to be extremely low in the case of WZ Sge.

If \( r_{\text{tr}} \) in (some) BSXTs is such that in quiescence the outer thin disk is globally stable the same reasoning would apply also to these systems and (some) SXT outbursts could be due to an EMT triggered disk instability.

4.2. Thermal instability in the outer thin disk

If, for a given mass transfer rate, the inner radius of the outer thin accretion disk \( r_{\text{tr}} \) is smaller than the critical radius \( r_{\text{crit}} \), the disk will be globally unstable and will undergo DN type outbursts. We show in this section that we obtain reasonable recurrence times without any unusual assumption about the value of the viscosity parameter \( \alpha_t \).

In order to estimate properties of the outbursts we closely follow the steps used by Smak (1993) in the analysis of WZ Sge.

As discussed in Section 2., the disk outburst begins when the density exceeds somewhere the critical value \( \Sigma_{\text{max}} \). The type of resulting outburst depends on where in the disk this happens. For a constant \( \dot{M}_T \), the type of outburst depends on two characteristic times: the time \( t_{\text{accum}} \) it takes the matter accumulating at the outer disk to build up a surface density larger than \( \Sigma_{\text{max}} \), and the viscous time \( t_{\text{vis}} \) which measures the time it takes matter to diffuse inward and cross the \( \Sigma_{\text{max}} \) barrier somewhere nearer to the inner disk boundary. If \( t_{\text{vis}} > t_{\text{accum}} \) one obtains a so-called “outside-in” (‘type A’) outburst beginning at the outer disk edge; in the opposite case one has an “inside-out” (‘type B’) outburst (Smak 1984).

Below, we will consider “inside-out” outbursts. As discussed by Smak (1993) these outbursts have longer recurrence times (longer length of the outburst cycle) than the “outside in” outbursts and give also upper limits on \( \alpha_t \). One should note here that although there are cases where it is claimed that BSXT outbursts began in the inner regions (Chen et al. 1993), the observational evidence is far from being conclusive. One should note however that the present discussion concerns the outer thin disk so that even an “inside-out” outburst in the outer disk would most probably be an “outside-in” outburst from the point of view of the inner, hot accretion flow.

Rescaling Eq. (5) to the characteristic parameters of the outer disk we get

\[
\dot{M} \approx 2.3 \times 10^{34} \left( \frac{\alpha_t}{0.01} \right)^{-0.79} \left( \frac{\dot{M}}{10^{14}} \right)^{2.74} \left( \frac{r_{\text{tr}}}{10^4} \right)^{3.11} \left( \frac{t_9}{t_{\text{vis}}} \right) g \text{ s}^{-1}. \tag{7}
\]

As before, \( \alpha_t \) denotes the viscosity parameter in the thin disk. If we replace \( \dot{M} \) by the luminosity of the thin disk:

\[
L_{\text{disk}} \approx \frac{G M \dot{M}}{R}, \tag{8}
\]

the recurrence time of the instability can be written as

\[
\left( \frac{t_{\text{rec}}}{10^3 s} \right) \approx \left( \frac{\alpha_t}{0.01} \right)^{0.79} \left( \frac{L_{\text{disk}}}{10^{41} \text{ erg s}^{-1}} \right)^{-1} \left( \frac{M}{10^6} \right)^{2.74} \left( \frac{r_{\text{tr}}}{10^4} \right)^{2.11}. \tag{9}
\]

Eq. (9) reveals the severe problem faced by the dwarf-nova type disk instability model of SXTs and how the problem is resolved in the NMY two-zone model. If we set the inner edge of the thin disk to be \( r_{\text{tr}} = 3 \), corresponding to the last stable orbit, then for the observed X-ray luminosity of \( \sim 10^{31} \text{ ergs s}^{-1} \), Eq. (9) shows that we need an absurdly small \( \alpha_t \sim 10^{-12} \). On the other hand, if we set \( r_{\text{tr}} \sim 10^3 \) as found by NMY from their spectral fits, then we obtain the right recurrence timescale with \( \alpha_t \sim 10^{-3} - 10^{-2} \), consistent with the values of \( \alpha_t \) required by the ‘standard’ DIM for dwarf novae (Livio & Spruit 1991). However, our estimated value of \( \alpha_t \) is very sensitive to the values of \( r_{\text{tr}} \) and \( m \), so that the values \( L_{\text{disk}}, r_{\text{tr}} \) and \( m \) cannot be much different from those assumed in Eq. (9) for \( \alpha_t \) to be not much smaller than \( 10^{-3} \). In the case of A0620-00 the optical luminosity is \( \sim 5 \times 10^{32} \text{ erg s}^{-1} \) (McClintock et al. 1995) so that if one wished to keep \( \alpha_t \sim 0.01 \), Eq. (9) requires \( r_{\text{tr}} > 10^4 \). At \( r = 10^4 \) this optical luminosity corresponds to an accretion rate \( \sim 10^{16} \text{ g s}^{-1} \). Fig. 3 shows however that for \( r_{\text{tr}} > 10^4 \) the outer disk is globally stable so that Eq. (9) does not apply because to go into outburst the system requires an EMT. On the other hand, if we allowed the value of \( \alpha_t \) to be as low as \( 5 \times 10^{-5} \), which is required for the pure DIM to work in the case of WZ Sge (Smak 1993), the transition radius could be \( r_{\text{tr}} \sim 10^3 \) depending on the value of the black hole mass.

We thus conclude that BSXT outbursts can be triggered by the ‘normal’ dwarf nova type instability in the outer cold, Keplerian disk. The critical factor which allows us to obtain good agreement on the recurrence time with a “reasonable” value of \( \alpha_t \) is the truncation of the thin disk at a large radius \( r_{\text{tr}} \). Since such values of \( r_{\text{tr}} > 10^4 \) are also required by the EMT model, this could be viewed as an independent confirmation of the truncated disk model of NMY.

5. Discussion

5.1. Spectral evolution during outburst

Another feature of the NMY model is that it provides a natural explanation for the spectral evolution seen in SXTs during outburst (Narayan 1996). When the outer disk goes into outburst and the mass accretion rate increases suddenly, the first response of the system will be for the \( \dot{M} \) in the inner advection-dominated zone also to increase proportionately. Since the luminosity of the inner zone varies roughly as \( \dot{M}^2 \), the X-ray luminosity will go up enormously. At the same time, since the electron temperature is very high, the spectrum will remain hard.
and there will be emission out to a few ×100 keV. Model calculations indicate that the photon spectral index is expected to be \( \sim 1.5 - 2 \) (Narayan 1996) when the luminosity reaches \( \sim 10^{-2}L_{\text{Edd}} \). Meanwhile, the increased \( M \) will probably cause the outer thin disk to diffuse inward on a viscous time. Therefore, after some delay, the outer thin disk will move into the advection-dominated zone, perhaps extending all the way into the black hole. When this happens, we will have a very luminous soft X-ray source with a spectrum consistent with that of a Shakura-Sunyaev disk. A0620-00 and Nova Muscae 1991 appear to have made this transition, whereas V404 Cyg remained a hard source throughout the outburst. Perhaps the thin disk did not penetrate all the way to the center in the latter case. As the outburst dies down, we expect these stages to occur in reverse. First, the thin disk will shrink back, leaving behind a strong hard X-ray source. Later, as \( M \) reduces, the system will revert to the quiescent state where there will be a very low X-ray luminosity and most of the viscous energy will be advected into the black hole. The stages described above, which appear reasonable under the advection-dominated model, match quite well with observations of several SXTs in outburst.

5.2. Difficulties

The NMY model gives a satisfactory description of the quiescent state of BSXTs, and as we have shown in this paper also provides a reasonable explanation of the recurrence times of the outbursts and the spectral evolution during outburst. All of these were difficult to explain with the previous model where the thin disk was assumed to extend all the way down to the black hole.

There is, however, an inconsistency in the NMY model. The spectral ‘fits’ are made under the assumption that the outer disk is stationary, which means in practice, that a temperature profile \( T_{\text{eff}} \sim r^{-3/4} \) is used to calculate the spectrum. For the parameters required for an acceptable spectral fit, the assumed values of \( M \), \( \alpha \), and \( r_{\text{tr}} \), are such that \( r_{\text{tr}} < r_{\text{crit}} \) so that a stationary disk is globally unstable. Such a disk would therefore be subject to the dwarf-nova type instability, which means that in the quiescent state the accretion rate would not be constant with radius. This implies a self-inconsistency in the NMY model.

A further problem arises from the \( T_{\text{eff}} \) required to fit the optical spectra. Taking for the effective temperature (cf. Frank et al. 1992)

\[
T_{\text{eff}}(R) = \left[ \frac{3GM}{8\pi\sigma R^3} \right]^{1/4},
\]

and replacing \( \dot{M} \) by the expression given in Eq. (3) we see that

\[
T_{\text{eff}}(r) \approx 2230 \left( \frac{\alpha}{0.01} \right)^{-0.2} m_{10}^{0.19} \left( \frac{r_{\text{tr}}}{10^4} \right)^{0.03} t_{9}^{-1/4} K, \]

which shows that the effective temperature in a quiescent dwarf nova disk is practically independent of the radius. For \( m = 1 \) and a recurrence time \( \sim 60 \) days, typical parameters of a dwarf nova, Eq. (2) gives \( (\alpha = 0.01) T_{\text{eff}} \sim 5400 K \), very close to the observed values (Wood et al. 1986).

The problem arises when we apply the same formula to quiescent SXTs. For SXT parameters, the effective temperature turns out to be \( \sim 2000 K \) which is too low to agree with observations. Both in A0620-00 and V404 Cyg, the optical and UV data imply significantly higher temperatures. It should be emphasized that this problem is not peculiar to the NMY model, but will be faced by any SXT model which invokes a dwarf nova type non-steady quiescent accretion disk.

A possible explanation for the higher disk temperature could be that the outer disk is optically thin. The strong H\( \alpha \) line in the spectra of these disks suggests that a substantial part of the emission comes from optically thin gas. It is then natural for the color temperature to be higher than the effective temperature.

Finally, one should note that the failure of the DIM to account for the properties of quiescent SXTs has been also noticed by Cannizzo et al. (1995) and Kim et al. (1996) who suggested ‘non-standard’ inner disk structures that do not invoke advection.

6. Conclusions

The detailed mechanism by which BSXTs go into outburst will depend on the values of \( M \), \( \alpha \) and \( r_{\text{tr}} \). These parameters, or rather the ratio \( \dot{M}/\alpha \) and \( r_{\text{tr}} \), are the free parameters which NMY used to fit their models to observed spectra of quiescent SXTs. The physical conditions in the outer disk are very similar to those that are encountered in accretion disks of SU UMa systems. For this reason also the problems with the origin of the outbursts (or rather superoutbursts) are the same.

At the low accretion rates that are required by observations of BSXTs in quiescence, the accretion disk may be globally stable for \( r \gtrsim r_{\text{tr}} \). In this case only an increase in the mass transfer from the secondary can bring the disk into an unstable state and trigger the outburst. To make the model complete one should find why the secondary increases its transfer rate on timescales typical of SXTs. One should note however that variations of the transfer rate on various timescales are observed in many close binary systems.

When \( \dot{M}, \alpha \) and \( r_{\text{tr}} \) correspond to a globally unstable outer disk configuration, a DN type instability will necessarily occur. The effect of the outburst on the inner hot ADAF should be similar to that of an EMT triggered outburst since both types of outbursts are basically due to the same thermal instability.
It is not impossible that both types of mechanisms are at work in BSXTs, in different systems and/or in the same systems but at different epochs.

The main result of this paper is that the disk instability model works much better for SXTs if the thin disk is truncated at a large transition radius $r_{tr}$ as in the NMY model rather than having the disk extending down to $r = 3$ as in the model by Mineshige & Wheeler (1989). The region inside the radius of truncation would then be filled with a very hot, optically thin, ultra-low radiative efficiency, advection-dominated flow. NMY showed that such a model gives a good fit to the spectra of quiescent SXTs, while Narayan (1996) suggested that it may be consistent with the spectral evolution observed in SXTs during outburst. In this paper, we show that the recurrence times of SXT outbursts are satisfactorily predicted with a reasonable value of the viscosity parameter $\alpha \sim 10^{-3} - 10^{-2}$ in the outer disk (or $\sim 10^{-5}$ in the worst case). In contrast, in the dwarf–nova type model, one requires an implausibly low value $\alpha \sim 10^{-12}$.

One interesting point to bear in mind is that it is possible to have binaries where $\dot{M}, \alpha$ and $r_{tr}$ correspond to a globally stable outer disk in a cold low state, and where in addition the secondary star for whatever reason does not have any tendency to exhibit a large amplitude EMT instability. In such a system, we would have a black hole binary which is permanently in the quiescent state, with most of the accretion energy being swallowed by the black hole. The system would be extremely dim in X-rays and quite under luminous even in the optical and would be very hard to detect. In principle, the Galaxy could have large numbers of such nearly silent black holes, which would be the binary equivalent of the underluminous galactic nuclei discussed by Fabian & Rees (1995).

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