Astron. Astrophys. 360, 575–582 (2000)

ASTRONOMY
AND
ASTROPHYSICS

X-rays from quiescent low-mass X-ray binary transients

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Received 6 March 2000 / Accepted 15 June 2000

Abstract. I argue that it is very unlikely that X-rays from quiescent black-hole low-mass X-ray binary transients are emitted by coronae of companion stars. I show that in a simple model in which these X-rays are emitted by an ADAF filling the inner part of an unsteady, dwarf-nova type disc, the X-ray luminosity is correlated with the orbital period. I predict what values of X-ray luminosities from black-hole transient systems should be observed by Chandra and XMM-Newton.

Key words: stars: binaries: close – accretion, accretion disks – instabilities – X-rays: general

1. Introduction

Low-mass X-ray binary transient systems (LMXBTs; these systems are also called 'X-ray novae' or 'Soft X-ray transients') are low-mass X-ray binaries (LMXBs) which sometimes (rarely for the most part) undergo outbursts during which the X-ray luminosity increases by more than 5 to 6 orders of magnitude. In LMXBs, a black hole or neutron star primary accretes matter lost by a Roche-lobe filling, low-mass secondary star. All known low-mass X-ray binaries (LMXBs) containing black holes are transient (Tanaka & Shibazaki 1996), whereas many neutron star LMXBs are steady, in the sense that unlike black-hole LMXBs they do not show high amplitude outbursts, but only low amplitude X-ray flux variation. Matter transferred from the secondary, forms an accretion disc, which far away from the accreting object is quasi-Keplerian. Accretion discs in LMXBTs appear to be truncated in their inner regions (Esin et al.1997; Życki et al. 1998, 1999). Since here magnetic fields can play no role (because the magnetic moments of neutron stars are too low, and because of the absence of black holes magnetic fields) the inner disc 'hole' can be due only to some kind of evaporation (Narayan & Yi 1995; Honma 1996). In such a case the inner accretion flow onto the compact object may form an advection-dominated accretion flow (ADAF; Abramowicz et al. 1995; Narayan & Yi 1995). Truncated discs are also required by the disc instability model (DIM), which is supposed to describe LMXBT outbursts (Lasota 1996; Menou et al. 2000; Dubus et al. 2000). This model was devised to describe dwarf nova (DN) outbursts (see Cannizzo 1993 and Lasota 2000b for reviews). Also in these systems truncated discs are required to reconcile models with observations (e.g. Lasota et al. 1999; Meyer & Meyer-Hofmeister 1994; Shaviv, Wickramasinghe & Wehrse 1999)

According to models of such truncated discs the inner accretion flow is an optically thin, very hot plasma, in which temperature may be close to the virial temperature. It is therefore expected to emit a considerable part of its energy in X-rays. This is indeed observed in quiescent DN and LMXBTs where such inner hot flows should be present (Eracleus et al. 1991; Richards 1996; van Teeseling et al. 1996; McClintock et al. 1995; Verbunt et al. 1994; Wagner et al. 1994; Asai et al. 1998; Barret et al. 1996). The properties of this X-ray emission provide an important test of accretion flow models (see e.g. Quataert & Narayan 1999; Meyer et al. 1996).

However, since observed X-ray luminosities are often rather low, one should be sure that the X-rays are not emitted by other sources, in principle less powerful than accretion. For DN it was shown that quiescent X-rays are emitted by the accretion flow and not by the secondaries coronae (Eracleus et al. 1991; van Teeseling et al. 1996; Richards 1996). For LMXBTs Verbunt (1996) concluded that ("except maybe for A0620-00") X-rays cannot be emitted by coronae of secondary stars. In the case of neutron-star LMXBTs Brown et al. (1998) attribute the quiescent X-rays to thermal emission from the neutron-star surface. This emission would be due to repeated deposition during the outbursts of nuclear energy deep in the crust. This could be a viable alternative to the accretion model (Rutledge et al. 1999, see however Menou et al. 1999c).

Recently Bildsten & Rutledge (1999) concluded that in the case of black-hole LMXTBs the quiescent X-rays may be due to coronal emission from stellar companions. They argue that in these systems the ratio of the X-ray flux to the stellar, bolometric flux is $\lesssim 10^{-3}$ as in RS CVn's, which are active, close, detached binaries of late-type stars (a G of K type giant or subgiant in orbit with a late-type main-sequence or subgiant) in which, for orbital periods $\lesssim 30$ days, the rotation of both components is synchronous with the orbit. Their coronal X-ray emission may be as large as 10^{31} erg s^{-1} (Dempsey et al. 1993).

Unfortunately, only three quiescent black-hole LMXBT systems were detected in X-rays. In A0620-00 the quiescent (~ 2 - 10 keV) luminosity is $L_X = 10^{31}$ erg s^{-1}, in the other two systems (GRO J1655-40 and V404 Cyg) $L_X > 10^{32}$ erg s^{-1}

(see Garcia et al. 1997 and references therein). This sample is not only small but also very eclectic as far as companion stars are concerned. The secondary in A0620-00 is a late type dwarf (K5V, McClintock & Remillard 1986), in GRO J1655-40 the F3-6 (Orosz & Bailyn 1997) secondary is either near the end of its main-sequence life (Regös et al. 1998) or is crossing the Hertzsprung gap on its way to the giant branch (Kolb et al. 1997; Kolb 1998), and finally in V404 Cyg the K0 (Casares et al. 1992) secondary is a 'stripped' giant (King 1993). In the case of the last system Bildsten & Rutledge (1999) admitted that its $L_X = 1.6 \times 10^{33}$ erg s^{-1} cannot be emitted by the companion's corona (they find $L_X/L_{\rm bol} = 8 \times 10^{-2}$). However, except for this system and for 4U1543-47 (see below), Bildsten & Rutledge (1999) expect quiescent X-ray luminosity of black-hole LMXTBs to originate in the coronae of secondaries.

I discuss this hypothesis in Sect. 2. and conclude that it cannot be correct. Black-hole LMXBT's secondary stars cannot be the source of quiescent X-rays because they are not different from their dwarf nova counterparts. In the (two known) cases where these secondaries are different, their coronal X-ray luminosity should be lower than in the corresponding active star binaries, so that also in this case quiescent X-ray luminosity can only result from accretion. In Sect. 3 I discuss what the disc instability model of dwarf novae and LMXBTs has to say about quiescent X-ray emission and in Sect. 4 I show that, on simple assumptions, this model combined with an ADAF model (as first proposed by Narayan et al. 1996; see also Lasota et al. 1996) predicts a correlation between the quiescent X-ray luminosity and the orbital period. This correlation is satisfied by the three observed systems, which allows one to make predictions about future observations by Chandra and XMM-Newton of systems for which up to now only upper limits are known. Sect. 5 ends the article with discussion and conclusions.

2. Companion stars

Roche-lobe filling, secondary stars in close binaries are rapidly rotating stars, so their coronae can be rather powerful X-ray emitters by 'normal' star standards, and one could think that they could explain the quiescent X-ray emission in some close binaries (e.g. Charles 1996). However, for dwarf novae, and CVs in general, this does not seem to be possible (Ruciński 1984a; Eracleus et al. 1991; Richards 1996). Observations of rapidly rotating late type stars suggest a saturation of X-ray luminosity at approximately (Fleming et al. 1989)

$$L_{\rm X} \approx 10^{29} \left(R/10^5 {\rm km}\right)^2 \ {\rm erg\ s}^{-1}. \qquad (1)$$

Using the relation (Paczyński 1971)

$$R_2 = 0.462 \left(\frac{M_2}{M_1 + M_2}\right)^{1/3} a \qquad (2)$$

$$a = 3.5 \times 10^{10} \left(\frac{M_1}{M_\odot}\right)^{1/3} (1+q)^{1/3} P_{\rm hr}^{2/3} \ {\rm cm}, \qquad (3)$$

where M_2 and R_2 are respectively the secondary's mass and radius, q is the secondary to primary mass-ratio, $P_{\rm hr}$ the orbital period in hours, one obtains

$$L_{\rm FGM} = 2.7 \times 10^{29} M_2^{2/3} \ P_{\rm hr}^{4/3}. \qquad (4)$$

Therefore, coronal X-ray emission from rapidly rotating stars has to obey the inequality

$$L_X < L_{\rm FGM}. \qquad (5)$$

This observed saturation effect is to be expected on theoretical grounds (Vilhu 1984; Vilhu & Walter 1987; Skumanich 1986; Skumanich & MacGregor 1986). Coronal activity and coronal heating are thought to be of magnetic origin. They depend on the star's rotation speed and on the depth of the convection layer under the stellar surface.

As first pointed out by Ruciński (1984a) the relevant measure of coronal activity is the ratio of the X-ray to bolometric luminosity $L_X/L_{\rm bol}$. This ratio increases with stellar rotation but gets saturated at around 10^{-3} (see e.g. Singh at al. 1999). However, as shown both by observation and by models (Fleming et al. 1989), this saturation is a surface effect: the number of magnetic loops grows until there is no more space for new ones to appear. As a result the X-ray luminosity saturates at the limit given by Eq. (1). That is why secondary stars in CVs and LMXBs cannot, despite their fast rotation, be powerful X-ray emitters: they are just too small (see also Eracleus et al. 1991).

To illustrate the meaning of the saturation effect let us consider two cases of rapidly rotating active stars. The very rapidly rotating ($P = 9.12$ hr) K2V star called Speedy Mic (HD 197890) has $L_X/L_{\rm bol} = 8.5 \times 10^{-4}$ but its X-ray luminosity is only 8.7×10^{29} erg s^{-1} (Singh et al. 1999), in complete agreement with Eq. (1). The 12.5 hr pre-cataclysmic binary V471 Tau with a K2V secondaryhas $L_X/L_{\rm bol} > 10^{-3}$ (Ruciński 1984b). Wheatley (1998) showed that the hard uneclipsed X-ray luminosity may be due to a coronal activity of the secondary since for this component $L_X/L_{\rm bol} \approx 10^{-3}$ (the other component results from wind accretion onto the white dwarf), but its X-ray luminosity is $\sim 10^{30}$ erg s^{-1} in total agreement with Eq. (1). Therefore, if for a given system $L_X/L_{\rm bol} \approx 10^{-3}$ and the X-ray luminosity is larger than the limit given by Eq. (1) (or Eq. (4)), one should rather conclude that this luminosity cannot be due to the coronal activity of the secondary.

The limit given by Eq. (4) (with $M_2 = 1 M_\odot$) is plotted in Fig. 1, which in addition to X-ray luminosities of DN (Eracleus et al. 1991) and LMXBTs (Garcia et al. 1997 and references therein) shows X-ray luminosities (Dempsey et al. 1993) of RS CVn stars. Clearly, X-ray luminosities of all RS CVn stars are below this limit, whereas X-ray luminosities of dwarf novae (Eracleus et al. 1991) and LMXBTs (Verbunt 1996) are above it. One can conclude, therefore, that the X-ray luminosities from quiescent DN and LMXBTs are too large to be emitted by coronae of stellar companions.

The conclusion about DN was confirmed by observations of eclipsing systems in which X-rays are clearly emitted near the white dwarf (Wood et al. 1995; van Teeseling 1997).

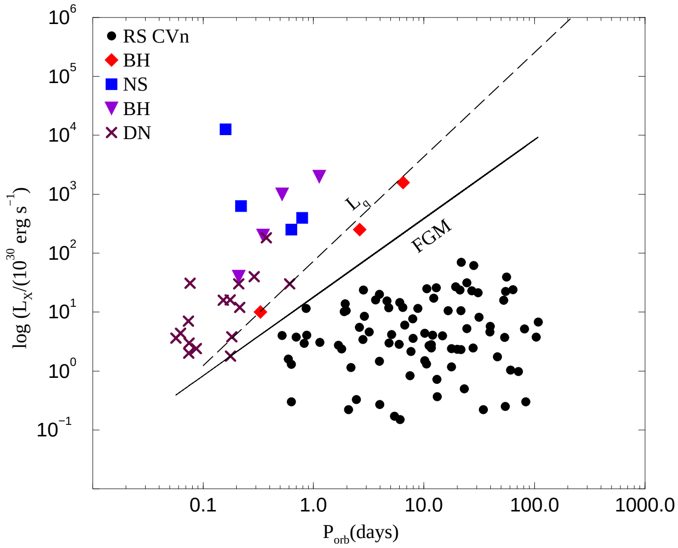

Fig. 1. X-ray luminosities of quiescent dwarf-novae and soft X-ray transients and X-ray luminosities of RS CVn stars. The continuous line marked 'FGM' is the limit given by Eq. (4) with $M_2 = 1M_{\odot}$. The dashed line corresponds to the relation Eq. (13). Down-pointing triangles correspond to upper limits.

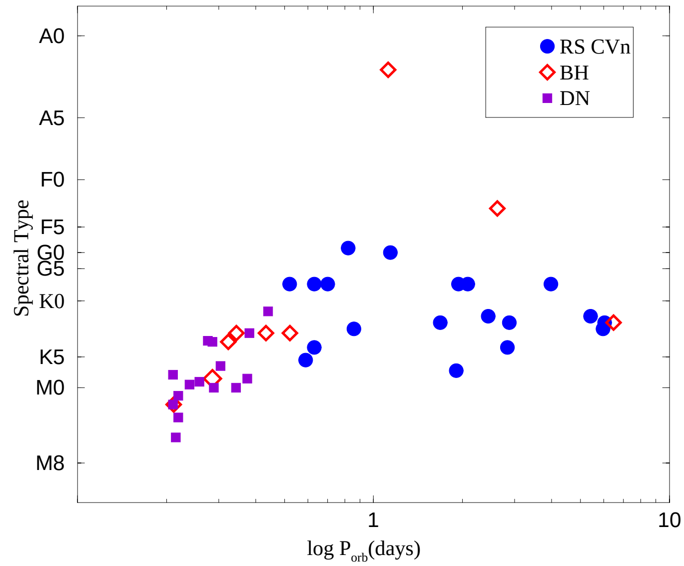

Fig. 2. Spectral types of secondary stars of dwarf novae, black -hole X-ray transients and of RS CVn stars

Recently, however, Bildsten & Rutledge (1999) challenged the validity of this conclusion for black-hole LMXTBs. They estimate the ratio of X-ray to bolometric luminosity in quiescent black-hole LMXTBs to be $\sim 10^{-3}$, close to the maximal one observed in RS CVn stars. They argue, however, that the actual X-ray luminosity of black-hole LMXBT's secondaries may be larger than in RS CVn because they would be at a given orbital period, of an earlier spectral type. According to the same authors the $L_X/L_{\rm bol}$ ratio in both DN and neutron-star LMXTBs is too high ($\gg 10^{-3}$) for the X-rays to be emitted by stellar coronae, which confirms previous conclusions.

Even if secondaries in black-hole LMXTBs were of an earlier type than, say CVs, this would not help much because the saturation value of L_X depends mostly upon radius and not on the effective temperature (Fleming et al. 1989). In any case, as I show below, if black-hole LMXBT's secondaries were different from CV's companions at the same orbital period, they would rather be of a later type.

Fig. 2 shows the spectral types of stellar companions as a function of the orbital period, for dwarf novae, black-hole LMXTBs and selected RS CVn stars. Dwarf nova data are taken from Beuermann et al. (1998) where I selected only systems with orbital periods longer than ~ 5 hr. black-hole LMXTBs spectral types are the same as in Bildsten & Rutledge (1999) and the spectral type of GRS1009+45 (X-ray Nova Velorum 1993) is taken from Filippenko et al. (1999). From Dempsey's et al. (1993) Table 1, I chose systems of the latest type, in order to maximize the 'chances' of the assertion according to which secondaries in black-hole LMXTBs are of earlier type. I took the same attitude towards the error bars or spectral type ranges, choosing the latest possible for DN and RS CVn's and the earliest for black hole systems. The statistics is rather poor since only nine black-hole LMXTBs have known orbital periods. Fig. 2 shows that except for two systems, 4U 1543-47 (A2) and GRO J1655-40 (F3), all the other systems (i.e., the other six) have spectral types similar to that of DN and RS CVn's at the same orbital period. Considering that I have chosen the earliest possible spectral types for LMXBTs and the latest possible for the other systems, one could conclude that LMXBT secondaries are of later type.

The two odd systems are less evolved than secondaries in RS CVn's and dwarf novae (not plotted here but known to contain subgiants or giants, see e.g. Warner 1995) at the same orbital period. These two systems, 4U 1543-47 and GRO J1655-40, are exceptional because their secondaries are much more massive than in other 'low mass' binaries. They are the only two systems (out of probably 12, see Kalogera 1999 and references therein) with intermediate mass ($\gtrsim 2M_{\odot}$) secondaries. 4U 1543-47 is in phase A of binary evolution, expanding away from the main sequence (Kolb 1998) and GRO J1655-40 is either close to the end of its main sequence life (Regös et al. 1998) or is crossing the Hertzsprung gap (Kolb et al. 1997; Kolb 1998). Late-type companions of RS CVn's are probably crossing or have already crossed this gap (Popper & Ulrich 1977). The A2 secondary in 4U 1543-47 is, anyway, not a very good candidate for an active star (as also acknowledged by Bildsten & Rutledge) since e.g. its Rossby number, measuring stellar activity, is rather large (in simpler terms: there is no convective envelope to speak of). The situation of GRO J1655-40 is not much better since, as shown by Fleming et al. (1989), the saturation X-ray flux for $B-V < 0.6$ steadily decreases with increasing stellar mass. Therefore, the fact that for this system $L_X/L_{\rm bol} \sim 10^{-3}$ would rather suggest that X-rays are not due to stellar activity.

Until recently it has been thought that companion stars in CVs are, with a few exceptions, indistinguishable from main-sequence stars (see e.g. Warner 1995). Recent, detailed com-

Table 1. Predicted X-ray fluxes

System (1)	$P_{\rm orb}$ (2)	D (3)	logN_H (4)	Flux (5)	Chandra counts (6)	XMM counts (7)
GRO J0422+32	5.1	2.6[1]	21.3	0.6	$25^{(a)} - 15^{(b)}$	$70^{(a)} - 105^{(b)}$
GRS1009-45	6.9	5[2]	21.05	0.3	$15^{(a)} - 5^{(b)}$	$35^{(a)} - 50^{(b)}$
GS2000+25	8.3	2.7	21.92	1.3	$25^{(a)} - 5^{(b)}$	$85^{(a)} - 45^{(b)}$
GS1124-683	10.4	5	21.21	0.6	$25^{(a)} - 15^{(b)}$	$75^{(a)} - 130^{(b)}$
H1705-250	16.8	8.6	21.44	1.3	$45^{(a)} - 20^{(b)}$	$135^{(a)} - 165^{(b)}$
4U 1543-47	27.0	8	21.44[3,4]	1.2	$40^{(a)} - 20^{(b)}$	$125^{(a)} - 150^{(b)}$
A 0620-00†	7.8	1.2	21.29	5.8	$230^{(a)} - 135^{(b)}$	$620^{(a)} - 1150^{(b)}$
GRO J1655-40♣	62.9	3.2	21.8	20.5	$410^{(a)} - 130^{(b)}$	$1540^{(a)} - 970^{(b)}$
V404 Cyg♠	155.3	3.5	22.4	108	$1240^{(a)} - 130^{(b)}$	$4400^{(a)} - 1032^{(b)}$

$^{(a)}$ Photon power-law index = 1.5
$^{(b)}$ Photon power-law index = 3.5
(1) Only the last three systems were detected by previous instruments
(2) Orbital periods in hours (see Menou et al. 1999c and references therein and Filippenko et al 1999).
(3) Distances to the systems in kpc (see text).
(4) Logarithm of the column density
(5) Unabsorbed X-ray flux in 10^{-14} erg cm^{-2} s^{-1} from formula Eq. (13).
(6) For Chandra ACIS-S, integrated over 50 ksec.
(7) For XMM - Newton EPIC PN, integrated over 50 ksec (per one instrument)
[1] Esin et al. (1998)
[2] Barret et al. (2000)
[3] Orosz et al. (1998)
[4] Predehl & Schmitt (1995)
†photon-index ~ 3.5 from $ROSAT$ observations (Narayan et al. 1997)
♣photon-index ~ 1.5 from $ASCA$ observations (Hameury et al. 1997)
♠photon-index ~ 2.1 from $ASCA$ observations (Narayan et al. 1997)

parison of the observed properties of CV's secondaries with main sequence (MS) field stars showed that, for orbital periods $\gtrsim 6$ hours, a considerable fraction of CV's companions are evolved (Baraffe & Kolb 1999, 2000; Beuermann et al. 1998; Beuermann 1999). At a given orbital period these evolved secondaries are therefore cooler than a hypothetical main sequence star (i.e. of an later spectral type at a given orbital period). There is no known reason why secondaries in black-hole LMXTBs should have very different properties (e.g. King 1999), which is confirmed by Fig. 2. Therefore, if coronal emission from secondaries cannot be the source of X-rays in CVs, the same is true of black-hole LMXTBs, as suggested in any case by Figs. (1) and (2). Therefore, X-ray emission from black-hole LMXTBs must be produced directly by accretion. The same is not necessarily true for neutron-star LMXTBs as proposed by Brown et al. (1998). I will come back to this problem in Sect. 5.

All of this does not mean that secondary stars in LMXBTs are not active (Ruciński 1984b). They should be active, at least for short period systems whose evolution is supposed to be driven by magnetic braking. But their X-ray luminosity is what is expected from such stars: too weak to explain observations of quiescent LMXBTs.

The quiescent X-ray luminosity may vary by a factor $\gtrsim 3$ in few days (in Cen X-4, see Campana et al. 2000 and references therein) or by a factor ~ 3 and ~ 10 in A0620-00 and V404 Cyg respectively (McClintock private communication) on a not yet determined timescale. Such variations are not unexpected in an ADAF, but as pointed out by Campana et al. (2000) they could also be due to giant flares in coronae of secondary stars. Such flares are observed in RS CVn's and Algol systems and their luminosity can reach $\sim 10^{32}$ erg s^{-1} (Ottmann & Schmitt 1996; Güdel et al. 1999). However, the hope expressed by Campana et al. (2000), that even more energetic flares should be expected from shorter period systems, is substantiated neither by models nor by observations (Audard et al. 2000).

3. Quiescent X-rays according to the disc instability model

There is reasonable evidence that both DN and LMXBT outbursts are triggered by the same physical mechanism: a thermal-viscous instability due to hydrogen recombination at the disc's effective temperature $5500\ \mathrm{K} \lesssim T_{\rm eff} \lesssim 7500$ K. Any disc in which the effective temperature is at some point in this instability strip, will be subject to some kind of outburst. The presence of thermal instability does not by itself guarantee that outburst properties will agree with observations. Several ingredients must be added to the disc model in order to obtain outburst cycles which have anything to do with reality (e.g. Smak 1984, 1999; Liu et al. 1997; Hameury et al. 1998; Hameury et al. 2000; Menou et al. 2000; Osaki 1996). In LMXBTs disc X-ray irradiation is particularly important, as pointed out by van Paradijs (1996) and elaborated by King & Ritter (1998), Dubus et al. (2000) (see also Lasota 2000b) and Esin et al. (2000).

According to all versions of this disc instability model the outburst cycle is due to the disc oscillating between a cold quiescent state and, in outburst, a hot, fully ionized configuration. In quiescence the whole disc must be in the cold state. Such a quiescent disc is not in viscous equilibrium (which is the very reason for the outbursts), i.e. the accretion rate is not constant with radius and the matter transferred by the secondary accumulates in the disc. The presence of a non-steady disc in quiescent DN is confirmed by observation of eclipsing systems, which show flat effective temperature profiles (Wood et al. 1986, 1989, 1992; Rutten et al. 1992) as predicted by the model (Smak 1984).

In the DIM the accretion rate in quiescence must satisfy the inequality (e.g. Hameury et al. 1998)

$$\dot M_{\rm quie}(R) \ < \ \dot M_{\rm crit} = 4.0 \ \times \ 10^{15} \left(\frac{M}{M_\odot}\right)^{-0.88} \left(\frac{R}{10^{10}{\rm cm}}\right)^{2.65} \ {\rm g\,s^{-1}} \qquad (6)$$

where I omitted a term very weakly dependent on the viscosity parameter α.

This means that in quiescence the rate of accretion at the last stable orbit around a black hole or neutron star primary must satisfy

$$\dot M < \dot M_{\rm quie} \approx 3.6 \times 10^4 \left(\frac{M}{M_\odot}\right)^{1.77} \left(\frac{R}{3R_{\rm G}}\right)^{2.65} \ {\rm g\,s^{-1}}, \ (7)$$

where $R_G = 2GM/c^2$ is the Schwarzschild radius. These accretion rates are much lower than the mass transfer rates from secondaries.

In terms of accretion luminosities this implies the following limit:

$$L_{\rm accr} \lesssim 6.6\times 10^{24} \left(\frac{\eta}{0.1}\right) \left(\frac{M}{M_\odot}\right)^{1.77} \left(\frac{R}{3R_{\rm G}}\right)^{2.65} {\rm erg\ s^{-1}} (8)$$

for LMXBTs (where η is the accretion efficiency). Fig. 1 shows observed X-ray luminosities from quiescent dwarf novae and X-ray transients. For all LMXBTs these luminosities are much higher than the limits given by Eqs. (8). (It is sometimes claimed that the quiescent X-ray luminoisties are much lower than expected. Such claims assume, that the quiescent disc is stationary which, obviously, is not the case.) If observed X-rays are emitted by the accretion flow in the vicinity of the central compact body then the cold quiescent accretion disc whose presence is required by the DIM cannot extend down to the central compact body (Meyer & Meyer-Hofmeister 1994; Mineshige et al. 1992; Lasota 1996).

The DIM can be reconciled with X-ray observations if the quiescent disc is truncated at some radius $R_{\rm tr}$ as proposed by Meyer & Meyer-Hofmeister (1994) for DN and by Narayan et al. (1996) for LMXTs. For DN $R_{\rm tr} > R_{\rm WD}$ where $R_{\rm WD}$ is the white dwarf's radius, for LMXTs $R_{\rm tr} >> R_G$. In the case of Narayan et al. (1996) the motivation was different: they realized that X-ray, UV and optical spectra of quiescent black-hole LMXTBs cannot be reproduced by a standard model (Shakura & Sunyaev 1973) in which the accretion disc reaches down to the last stable orbit but are well represented by a model in which the inner part of the disc is replaced by an ADAF. The two aspects of the problem, the DIM and the spectra, have been taken into account by Lasota et al. (1996), Narayan et al. (1997), Hameury et al. (1997) for black-hole LMXTBs and by Meyer et al. (1996) for DN.

During outbursts the inner disc radius reaches the last stable orbit and then recedes to its quiescent position (Esin et al. 1997; Życki et al. 1998, 1999; Menou et al. 2000; Dubus et al. 2000). In the main body of the quiescent disc (not too close to the outer boundary) the accretion rate radial profile is roughly parallel to the critical rates, i.e. its radial slope is ~ 2.6. Of course, this profile changes and the accumulating matter creates somewhere a bump which will trigger an outburst by crossing the $\dot M_{\rm crit}$ line. However, for systems with very long recurrence times, such as black-hole LMXTBs, one can consider that during quiescence the accretion rate radial profile is parallel to the critical one. This results from the roughly self-similar character of the decay from outburst produced by the cooling wave. As a result, at a given radius (not too close to the outer boundary) the disc state always ends up at the same place on the S-curve (see Menou et al. 1999b, especially Fig. 9).

One can therefore estimate the accretion rate at the truncation (transition) radius just by rescaling Eq. (6) to typical parameters and one obtains

$$\dot M \approx \dot M_{\rm tr} \approx 2.4\times 10^{15} \left(\frac{M}{7M_\odot}\right)^{1.77} \left(\frac{R_{tr}}{10^4 R_{\rm G}}\right)^{2.65} \ {\rm g\,s^{-1}}. (9)$$

Because of the strong dependence on R this is quite a good estimate of the actual accretion rate, as I will argue in the next section. On the other hand, to make the formula operational one has to decide what (or where) R_{tr} is.

4. X-rays from ADAFs in quiescent black-hole LMXTBs

The main problem of the accretion-disc+ADAF model is the absence of a satisfactory description of the transition between the two flows. Although substantial advances have been made in this domain (Kato & Nakamura 1999; Liu et al. 1999; Manmoto et al. 2000) the value of the transition radius is still rather a free parameter than a well determined physical quantity. Spectral models of quiescent black-hole LMXTBs suggest a value of the transition radius $R_{\rm tr} \gtrsim 10^4 R_G$ (Narayan et al.1997; Hameury et al. 1997; Quataert & Narayan 1999). The same result is obtained when one models outbursts of LMXBTs (Hameury et al. 1997; Menou et al. 2000; Dubus et al. 2000).

Menou et al. (1999a) found a simple prescription for the transition radius and used it rather successfully to describe the stability properties of LMXBTs. They noticed that the ADAF part of the flow should not extend to radii larger than the impact radius of the stream of matter that is being transferred from the secondary. The cold incoming stream would form an annulus at the impact radius $R_{\rm impact}$. One can expect that this material will spread a little under the influence of viscous evolution before it evaporates fully. Thus one expects $R_{\rm tr} \lesssim R_{\rm impact}$, i.e. a transition radius close to the ring formed by the transferred matter.

This is equivalent to assuming that in quiescence, the inner disc will evaporate up to the largest radius allowed by the mass-transfer stream. I will call this hypothesis 'Maximum ADAF Hypothesis' (MAH). The term 'strong ADAF principle' is sometimes used, but here this is not a principle, but just a hypothesis which, as I show below, can be tested by observations.

Calculations (Lubow 1989) show that the transferred stream may overflow the disc and converge to an impact radius which scales as $R_{\rm impact} \simeq 0.48 R_{\rm circ}$ (this coefficient corresponds to $q < 0.5$). The circularization radius around the accreting body $R_{\rm circ}$ can be approximated by (Frank et al. 1992):

$$\frac{R_{\rm circ}}{a} = (1+q)[0.5 - 0.227 \times \log q]^4. \qquad (10)$$

Menou et al. (1999a) put therefore

$$R_{\rm tr} = f_t\, R_{\rm circ}, \qquad f_t < 0.48. \qquad (11)$$

and showed that observational data (widths of H_α lines) are consistent with $f_t \approx 0.25$ for most systems, except for V404 Cyg where a value of $f_t \lesssim 0.1$ is required.

According to Eqs. (11), (10) and (3)) the transition radius depends on the orbital period of the binary system. On the other hand, as explained in the preceding section, the accretion rate at the transition radius, where the cold quiescent accretion ends, is a function of this radius. Therefore, by combining Eq. (9) and Eq. (11) one obtains the following relation:

$$\dot M_{\rm ADAF} \approx 1.6 \times 10^{18} f_t^{2.65} P_{\rm day}^{1.77} \,{\rm g\, s^{-1}} \qquad (12)$$

where $\dot M_{\rm ADAF}$ is the rate at which matter enters the ADAF from the cold quiescent disc. This rate is independent of the primary's mass. The transition radius $R_{\rm tr}$ is sufficiently distant from the outer disc's edge for the Eq. (9) to be valid.

Fig. 1 shows that the X-ray luminosities of the three detected quiescent systems satisfy a similar relation

$$L_X \approx L_q = 7.3 \times 10^{31} P_{\rm day}^{1.77} {\rm erg\, s^{-1}}. \qquad (13)$$

Of course, Eq. (12) deals with accretion rates, whereas Fig. 1 represents X-ray luminosities, so that Eqs. (12) and (13) suggest that the X-ray efficiency is

$$\eta_X \approx 5 \times 10^{-8} f_t^{-2.65}. \qquad (14)$$

For a typical value of $f_t \sim 0.25$ (Menou et al. 1999a) the X-ray efficiency $\eta_X \sim 2 \times 10^{-6}$.

One can compare accretion rates (i.e. the X-ray efficiency) predicted by Eq. (12) with ADAF models for the three black-hole LMXTBs in which X-ray in quiescence were detected (Narayan et al. 1997; Hameury et al. 1997). This amounts to determining the values of f_t. These models are calibrated by the X-ray luminosity so this comparison is a good test of the validity of Eq. (12). I compared Eq. (12) with models of Narayan et al. (1997) and Hameury et al. (1997). (In Quataert & Narayan (1999) accretion rates are slightly lower.)

I obtain the same ADAF accretion rates (and X-ray efficiency)n for very reasonable values of f_t. For A0620-00 I get $0.1 \lesssim f_t \lesssim 0.3$, for V404 Cyg somewhat lower values: $0.06 \lesssim f_t \lesssim 0.1$, and for GRO J1655-40 $f_t \sim 0.12$. As mentioned above, the necessity of a lower value of f_t for V404 Cyg based on H_α line widths was already pointed by Menou et al. (1999a) which is rather comforting but not a proof of the validity of my very simple model. This model, however, allows one to make predictions about future X-ray observations of known black-hole LMXTBs which until now escaped detection. The prediction is very simple: all quiescent X-ray luminosities should be close to the line L_q in Fig. 1.

I used W3PIMMS (http//heasarc.gsfc.nasa.gov) to calculate the number of counts that can be expected to be registered by Chandra and XMM-Newton. Results are presented in Table 1, in which I also included a similar estimate for the three systems detected by the previous X-ray missions. I consider two power-law spectral models with photon power-law indices 1.5 and 3.5. Distances and column densities are taken from Garcia et al. (1997), except when a different reference is given. GRO J0422+32, GRS1009-45 and GS1124-683 are at the detection limit for both satellites. A 21.5 ksec observation of GS2000+25 by Chandra (Garcia et al. 2000) failed to detect a single photon from this source which is consistent with estimates in Table 1, especially if the photon index is ~ 3.5 as in A0620-00 (Narayan et al. 1997).

One hopes, of course, that the distance determinations given in Table 1 are reliable.

5. Discussion and conclusions

The quiescent X-ray luminosity model is rather unsophisticated, but it is based on several natural properties of the ADAF + DIM-disc model of LMXTs and has the advantage of making definite predictions that, one might hope, will be tested by observations. Any detection of GRO J0422+32, H 1705-25, GS1124-68 would eliminate the coronal model, as pointed out by Bildsten & Rutledge (1999). The detection of all five systems close to the predicted fluxes would count as a success for the ADAF + DIM-disc model and in particular for the MAH (first suggested by Narayan & Yi 1995). One should keep in mind, however, that if the MAH were to apply in these systems this would not prove its general validity. In binaries the mass-transfer stream provides a a 'barrier' which prevents the spreading of evaporation. What would form such a barrier in galactic nuclei is not clear, but in NGC 4258 the ADAF extends only to few hundred R_G (Gammie et al. 1999, whereas it could in principle extend up to $\sim 10^4 R_G$).

The confirmation of correlation between X-ray luminosity and orbital period given by Eq. (13) would not necessarily mean that the inner, hot, accretion flow is an ADAF in the sense of Abramowicz et al. (1995) and Narayan & Yi (1995). This correlation means only that the rate at which accretion enters the hot flow is correlated with the size of the inner 'hole', hence with the orbital period. The 'standard' ADAF model is a good representation of the inner flow. It is not clear that it is only one.

More detailed observational diagnostics is required to decide what is the real solution.

Quiescent dwarf novae are not expected to satisfy Eqs. (12) or (13). First, most of them have recurrence times much shorter than black-hole LMXBs, so that the quiescent accretion rate should vary on a short time-scales. In fact X-ray quiescent luminosity is highly variable in these systems (Verbunt et al. 1999). Second, in many cases the inner disc truncation might be due to the action of the white dwarf's magnetic field rather than to evaporation (e.g. Lasota et al. 1999). In such a case the transition radius is just the magnetospheric radius and is independent of the orbital period.

In the case of neutron-star LMXTBs there are two possibilities. First, as proposed by Brown et al. (1998), the quiescent X-ray luminosity could be due to the neutron star surface being heated by thermonuclear reactions in the matter accreted during outbursts. In this case X-ray observations would allow the quiescent disc to extend down to the neutron star (or the last stable orbit). Second, as described in Menou et al. (1999c), the inner part of the quiescent accretion flow would form an ADAF as in black-hole LMXTBs. In this case the advected thermal energy must be emitted from the stellar surface so, for the same mass-transfer rate, quiescent neutron-star LMXTBs should be more luminous than those containing black holes, as observed. The problem, however, is that the model predicts quiescent neutron-star LMXTB luminosities much higher than observed. In order to reduce the accretion rate onto the neutron star (by three orders of magnitude) an ADAF model has, therefore, to involve the 'propeller effect' and perhaps the presence of winds (Menou et al. 1999c), so it is not as simple as the black-hole LMXBT models (see however Quataert & Narayan 1999). In this case, however, as in DN, one would not expect a correlation of the X-ray luminosity with the orbital period. Observations of variability of quiescent neutron-star LMXTBs could help in choosing the correct model. It is worth noting that simulations of outburst cycles of LMXBTs show that disc truncation is necessary if one wishes to reproduce observed properties of outburst cycles (Menou et al. 2000; Dubus et al. 2000).

For black-hole LMXTBs things are simpler: all available evidence suggests that quiescent X-rays are emitted by an ADAF filling the inner part of a truncated DIM-type accretion disc. A particular version of the model of such a configuration will be tested by Chandra and XMM-Newton.

Acknowledgements. I am grateful to Mike Garcia for very helpful advice and for information about Chandra observations prior to their publication. Comments and suggestions by Didier Barret, Guillaume Dubus, Jean-Marie Hameury, Erik Kuulkers, Jeff McClintock, Ramesh Narayan, Sławek Ruciński and Nick White were of great help. I thank Lars Bildsten and Bob Rutledge for interesting discussions which stimulated me to write this paper.

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