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ON THE ACCRETION INSTABILITY IN SOFT X-RAY TRANSIENTS

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ABSTRACT

Dwarf nova outbursts are likely caused by a thermal-viscous instability in the accretion disk around the white dwarf, which can occur if the mass transfer rate, $\dot{M}$, is below a critical value (which depends on orbital period). Based on data for soft X-ray transients and persistent low-mass X-ray binaries with known distances and orbital periods, $P_{\rm orb}$, I show that for these systems the distributions in a ($P_{\rm orb}$, $\dot{M}$) diagram can be understood with the dwarf nova instability criterion, if that is adapted to include X-ray heating of the disk. This supports the idea that the disk instability model applies to soft X-ray transients, and shows that X-ray heating must be included in modeling the outbursts.

Subject headings: accretion, accretion disks — X-rays: general

1. INTRODUCTION

Over the last several years, soft X-ray transients (SXTs) have become a subject of intensive studies, in particular because in most of them the compact star appears to be a black hole (see Tanaka & Lewin 1995 for a recent review). SXTs share with dwarf novae (DNs) the intermittent nature of the accretion, with relatively brief episodes of a high accretion rate ("outbursts") separated by relatively long periods in which the rate of accretion onto the compact object is low ("quiescence"), and it is only natural to assume that the same mechanism that gives rise to the unstable accretion is operating in both types of system.

Smak (1983) argued that the accretion in cataclysmic variables (CVs) is unstable if the rate of mass transfer from the secondary is below a critical value (that depends on the orbital period). White, Kaluzienski, & Swank (1984) pointed out that the time-averaged mass transfer rate of SXTs is systematically lower than those of the persistent low-mass X-ray binaries (LMXBs), and suggested that a mass transfer rate below a critical value ($\sim 10^{16.5}$ g s^{-1}) is a condition for the SXT instability to occur.

The mass flow through an accretion disk in a CV is stable if the temperature at the outer edge of the disk (at a radial distance from the white dwarf of 10^{10} $R_{d,10}$ cm), exceeds a critical value T_c given by $\log T_c = 3.9 - 0.1 \log R_{d,10}$ (Smak 1983; Osaki 1996). Corresponding to this is a critical mass transfer rate $\dot{M}_c$ that depends on the orbital period:

$$\dot{M}_c \simeq 2.7 \times 10^{17} (P_{\rm orb}/4 \text{ hr})^{1.7} \text{ g s}^{-1} . \qquad (1)$$

The locations of various types of CVs (e.g., the UX UMa, U Gem, SU UMa, and Z Cam systems) in a ($P_{\rm orb}$, $\dot{M}$) diagram are well described by this expression (Smak 1983; Osaki 1996).

2. RELATION BETWEEN ACCRETION RATE AND ORBITAL PERIOD FOR LMXBs

As I argue below, in the case of accreting neutron stars and black holes it is not the mass transfer rate by itself but the X-ray luminosity that determines the stability of the flow. To estimate the time-averaged X-ray luminosity, $\bar{L}_{\rm X}$, of SXTs, I have assumed that during quiescence the rate at which mass is transferred through the disk to the compact star is much smaller than the rate at which mass is transferred from the secondary onto the disk. Most of the mass accretes onto the compact object during the outbursts, so that $\bar{L}_{\rm X}$ is given by the ratio of the outburst energy and the average interval between outbursts. To calculate this ratio, we need an estimate of the distance d. Quiescent mass transfer rates derived on this assumption are in reasonable agreement with values obtained by Narayan, McClintock, & Yi (1996) from X-ray fluxes and spectra observed for quiescent black hole transients, using an advective accretion model with an efficiency for X-ray emission that is much lower that that of a "standard" disk accretion model.

For SXTs a distance estimate can be obtained from the properties of the secondary star in quiescence, if its late-type spectrum has been observed. This spectral type provides an estimate of the surface brightness of the secondary in a particular passband, e.g., the V band (Popper 1980); with the observed magnitude (corrected for interstellar extinction) this gives an estimate of the secondary's angular radius R_2/d. Since the secondary fills its Roche lobe, R_2 is obtained by combining Paczyński's (1971) expression for the ratio R_2/a (a is the orbital separation) and Kepler's third law, which gives $R_2^3 = 0.10(G/4\pi^2) M_2 P^2$, or $(R_2/R_\odot)^3 = 0.0128(M_2/M_\odot) P_{\rm hr}^2$. Thus, the derived distance depends weakly on the assumed mass of the secondary. For J1655−40 an independent distance (3.2 kpc) has been obtained from a relativistic model of the superluminal outflow (Hjellming & Rupen 1995), which agrees very well with that obtained from the optical properties of the secondary.

I have collected the available information (White et al. 1984; van Paradijs & Verbunt 1984; van Paradijs 1995) on distances, outburst fluences, and outburst intervals for SXTs with known orbital periods in Table 1, together with the average X-ray luminosity $\bar{L}_{\rm X}$ (in ergs s^{-1}) and the corresponding average mass transfer rate (for an assumed efficiency of $0.2c^2$ per gram of accreted matter). For J1655−40 I used data published by Hjellming & Rupen (1995), Bailyn et al. (1995a, 1995b) and Harmon et al. (1995).

Table 2 contains orbital periods and X-ray luminosities for persistent LMXBs with known distances. Two methods were used to determine distances: (1) For some X-ray burst sources the distance can be determined using X-ray fluxes observed

TABLE 1

SOFT X-RAY TRANSIENTS

Source	d (kpc)	P (hr)	ϵ_b (ergs cm^{-2})	Δt (yr)	$\log \bar{L}_X$	$\log \dot{M}_{av}$
J0422+32/XN Per 1992.............	2.5	5.1	0.25	>30	<35.3	<15.0
0620−000............................	0.8	7.8	2.9	50	35.2	14.9
1124−684/XN Mus 1991............	3.9	10.4	0.5	>30	<36.0	<15.7
1455−314/Cen X-4..................	1.8	15.1	0.1–1.4	15	35.1	14.8
J1655−40/XN Sco 1994.............	3.2	62.7	0.9	>30	<36.2	<15.9
1705−250/XN Oph 1977............	4:	16.8	0.2	>30	<35.6	<15.3
1908+005/Aql X-1	4.4	19.1	0.013–0.06	1.2	36.3	16.0
2000+251............................	2.5	8.3	0.9	>30	<35.8	<15.5
2023+338/V404 Cyg	8:	155.4	0.25	25	36.4	16.1

during the peaks of X-ray bursts which showed evidence for photospheric radius expansion; they then radiate at the Eddington luminosity (Lewin, van Paradijs, & Taam 1993, 1995), for which I have used a nominal value of 2×10^{38} ergs s^{-1}. (2) For Z-type sources (Hasinger & van der Klis 1989) there is persuasive (albeit model-dependent) evidence that they radiate close to the Eddington limit (Lamb 1989).

From Figure 1 it appears that the division between the steady (high mass transfer rates) and transient (low mass transfer rates) LMXBs with neutron stars is not well described by the relation that works so well for DNs. The reason is that the derivation of this expression presumes that the temperature in the disk is determined by the power generated locally in the disk, which is not a valid assumption for LMXBs. For the latter the energy budget is dominated by heating by X-rays, generated near the compact object, incident on the disk (van Paradijs 1983); the relative importance of X-ray heating becomes more important the larger the radial distance from the compact star is.

3. THE EFFECT OF X-RAY HEATING

I have derived a criterion for instability, starting from the DN criterion but assuming that the disk temperature is determined by X-ray heating. For the temperature T_0 at the outer edge of the disk, one then has (de Jong, van Paradijs, & Augusteijn 1996) $T_0^4 = (1 - \eta)(n - 1)(\tan\ \beta)L_X/(4\pi\sigma R_d^2)$. Here η is the X-ray albedo of the disk, β is the angular (semi-)thickness of the disk as seen from the compact star, and n is a constant that describes the thickness $h(r)$ of the disk through $h(r) = cr^n$; for X-ray–heated disks one has $n = 9/7$ (Vrtilek et al. 1990). In this expression for T_0 it is assumed that the X-rays arise from a point source in the center of the disk; this is likely a good approximation for a neutron star, but perhaps less so for a black hole where most of the flux originates in an annulus near the last stable circular orbit.

TABLE 2

PERSISTENT LOW-MASS X-RAY BINARIES

Source	P_{orb} (hr)	$\log \bar{L}_X$	$\log \dot{M}$
Sco X-1.............	18.9	38.3	18.0
1636−536	3.8	36.9	16.6
1735−444	4.65	37.6	17.3
1746−370	5.70	36.8	16.5
1820−303	0.19	36.9	16.6
1916−053	0.83	36.3	16.0
2127+119	17.1	36.1	15.8
Cyg X-2	236	38.3	18.0

Using $\eta = 0.92$, $\beta = 12°$ (de Jong et al. 1996), we obtain $\log T_0 = -4.79 + 0.25 \log L_X - 0.5 \log R_{d,10}$. Combining this with the DN instability criterion, one obtains $\log L_X = 34.8 + 1.6 \log R_{d,10}$.

One can relate the outer disk radius to the orbital period by assuming that the disk extends to a fixed fraction f (I have assumed $f = 0.8$) of the radius R_X of the Roche lobe of the compact star; the latter is given by (Paczyński 1971) $R_X/a = 0.38 + 0.2 \log (M_X/M_2)$. This expression is rather insensitive to the value of M_2; I have taken $M_2 = 0.4\ M_\odot$. Then for LMXBs with neutron stars ($M_X = 1.4\ M_\odot$), one finds the following relation dividing systems with stable and unstable mass transfer:

$$\log L_X = 35.2 + 1.07 \log P_{orb}\,. \tag{2}$$

For LMXBs with black holes (assumed $M_X = 10\ M_\odot$), one finds

$$\log L_X = 35.8 + 1.07 \log P_{orb}\,. \tag{3}$$

These relations are shown in Figures 1 and 2, respectively. They agree well with the observed separation of persistent LMXBs and SXTs. This result gives support to the idea that SXT outbursts are caused by an instability in the accretion disk, whose temperature is determined by X-ray heating. The

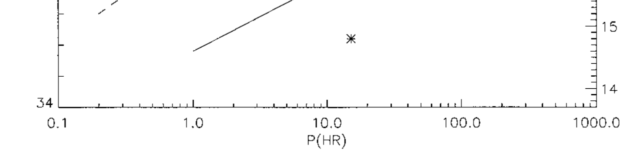

FIG. 1.—X-ray luminosity (and average mass transfer rate) as a function of orbital period for persistent and transient LMXBs with neutron stars. Filled circles indicate the persistent sources; the transients are indicated with asterisks. The dashed line indicates the separation between stable and unstable sources for cataclysmic variables (eq. [1]), the continuous line the relation derived here for neutron stars (eq. [2]). In converting accretion rate to X-ray luminosity, I have assumed a neutron star with mass $M = 1.4\ M_\odot$ and radius $R = 10$ km, corresponding to a radiation efficiency $GM/R \sim 0.2c^2$ ergs g^{-1}.

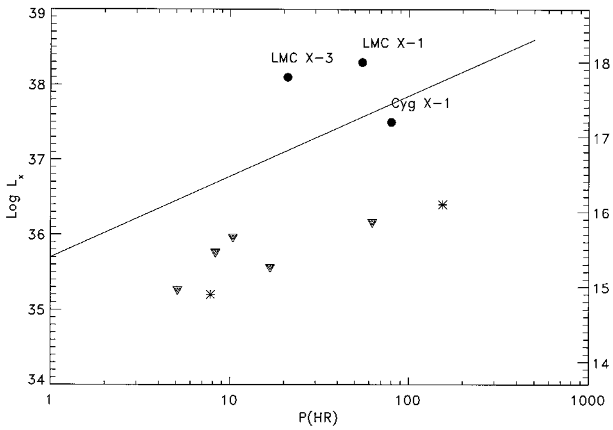

FIG. 2.—X-ray luminosity (and average mass transfer rate) as a function of orbital period for persistent and transient LMXBs with black holes. The transients with known recurrence times have been indicated with asterisks, the other transients with triangles. The straight line indicates the separation between persistent and transient sources derived here for black holes of 10 $M_\odot$ (eq. [3]). The figure also includes (*filled circles*) the three persistent high-mass X-ray binaries Cyg X-1, LMC X-1, and LMC X-3, at the fiducial positions that they would have occupied if they had been LMXBs with an equally large accretion disk, i.e., Roche lobe of the X-ray source. Since LMC X-1 and Cyg X-1 likely transfer mass by a (possibly focused) stellar wind instead of fully developed Roche lobe overflow, the radius of any accretion disk in these systems is likely to be smaller than the 80% of the Roche lobe radius assumed in the calculations (see text); as a result their fiducial positions are likely to be too far to the right in this diagram.

main effect of X-ray heating is to make the flow through the accretion disk stable down to substantially lower mass transfer rates than for DNs. It is interesting that the transient that is closest to the instability line is Aql X-1, also the one with (by far) the shortest outburst intervals.

The structure of X-ray–heated disks is different from those in CVs, e.g., the temperature profile is flatter than for CVs [$T(r) \propto r^{-3/7}$ instead of $T(r) \propto r^{-3/4}$; see Vrtilek et al. 1990]. It would appear that theoretical studies of SXTs, based on the disk instability model, should take this major effect into account; this implies some reservation with respect to results of studies that do not include X-ray heating as an integral part of the model (see, e.g., Cannizzo, Chen, & Livio 1995).

4. DISCUSSION

SXTs with neutron stars are relatively rare, but almost all LMXBs with black holes are transients. The above results indicate that the reason for this is that the black hole systems have very low mass transfer rates. Possible answers to the question why this is so may be found in the different evolutionary histories of these systems and in the effect of a larger mass of the accretor on the mass transfer rate.

It is striking that none of the time-averaged mass transfer rates in the BHXTs is far from 10^{-10} $M_\odot$, i.e., close to the value expected if gravitational radiation is the sole mechanism for loss of orbital angular momentum driving the mass transfer (Savonije 1983). This would suggest that in BHXTs loss of orbital angular momentum by magnetic braking (Verbunt & Zwaan 1981) is not very effective. For given M_2 and $P_{\rm orb}$ the replacement of a neutron star by a black hole will not directly influence the rate at which the secondary spins down due to magnetic braking. In the expression for the tidal torques (Campbell & Papaloizou 1983) the main factors $(M_1/M_2)^2$ and $(R_2/a)^6$ cancel each other, as can be seen by using Paczyński's (1971) expression for R_2/a. Thus, also the rate at which tidal torques keep the secondary star in corotation is not much affected by this replacement. Therefore, both in systems with black holes and in those with neutron stars, the secondary remains very close to corotation, and the corresponding rates of loss of orbital angular momentum do not differ much. However, for given M_2 and $P_{\rm orb}$, the orbital angular momentum of the systems with black holes is larger than that of systems with neutron stars by a factor $\sim(M_{\rm BH}/M_{\rm NS})^{2/3}$ (here $M_{\rm BH}$ and $M_{\rm NS}$ are the mass of the black hole and the neutron star, respectively), which equals $\sim$4 for a 10 $M_\odot$ black hole and a 1.4 $M_\odot$ neutron star. Since $\dot{M}/M_2 \sim \dot{J}_{\rm orb}/J_{\rm orb}$ (Savonije 1983), one expects the rate of mass transfer for a black hole system to be lower by this factor than that for the corresponding neutron star system. It remains to be seen whether this accounts for the observed low mass transfer rates in black hole transients.

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