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Long-term Variations of Soft X-ray Transients

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Abstract We concentrate on several items of long-term activity of soft X-ray transients (SXTs). The existence of known neutron star (NS) SXTs is not dependent on the orbital period $P_{\rm orb}$, which indicates a large scatter of the mass transfer rate in low-mass X-ray binaries of a given $P_{\rm orb}$. We investigate the role of irradiation of the disk on several examples of SXTs and show the cases when it evolves during outburst. We interpret the variations of the recurrence time $T_{\rm C}$ of outbursts of Aql X-1 and 4U 1608–52; the outbursts are triggered near the optically thin ADAF region and propagate outward in the disk. The outer disk region is brought to the hot state only in the rare, most intense outbursts. The amount of mass accreted largely varies for the individual outbursts in a given SXT. We also argue that the change of $T_{\rm C}$ in the Rapid Burster is caused by an increase of the disk viscosity. The cyclic modulation of $T_{\rm C}$ of GRS 1747–312 can suggest stellar activity of the donor. We interpret the so-called echo outbursts in KS 1731–260 as a series of outside-in outbursts, dependent on each other.

Key words: Stars: neutron — accretion, accretion disks — binaries: close — circumstellar matter — X-rays: binaries

1 INTRODUCTION

Low mass X-ray binaries (LMXBs) are close binary systems in which mass accretion from a late-type, lobe-filling star (donor) onto a neutron star (NS) or black hole (BH) occurs. Accretion process is the dominant source of their luminosity. The observed X-ray and optical activity, luminosity and spectrum of LMXBs crucially depend on the mass accretion rate onto the compact object, $\dot{m}_{\rm C}$. Inverse Compton scatter with the site in the close vicinity of the compact object is the dominant process for the X-ray radiation of LMXBs (see e.g. Lewin et al. 1995 for a review). Long-term activity of LMXBs is governed by the time-averaged mass transfer rate $\dot{m}_{\rm tr}$. Sufficiently low $\dot{m}_{\rm tr}$ leads to the thermal instability of the disk, which manifests as outbursts. Such LMXBs are called soft X-ray transients (SXTs). The outburst profile is modified by irradiation of the disk by X-rays from the vicinity of the compact object (e.g. King & Ritter 1998; Dubus et al. 2001).

We will concentrate on several important items of long-term activity of SXTs.

2 ORBITAL PERIODS AND THERMAL INSTABILITY IN LMXBS

The statistical distribution of the orbital periods $P_{\rm orb}$ of LMXBs, based on the data from the catalogue by Ritter & Kolb (2003) and its on-line updates (Fig. 1a), is asymmetrical with a tail toward long $P_{\rm orb}$. The observed LMXBs in general and NS transients appear to be most abundant near $P_{\rm orb} \approx 5$ hr. A rapid decrease of the distribution toward shorter $P_{\rm orb}$ is apparent for both groups. The period gap at $P_{\rm orb} \approx 1$ hr (Hameury et al. 1987) is visible, although it appears to be less pronounced than before. It can be seen from Figure 1a that the existence of NS transients is not dependent on $P_{\rm orb}$. This suggests a large scatter of $\dot{m}_{\rm tr}$ at a given $P_{\rm orb}$. The conditions in the donor are thus influenced by the processes operating on a time scale much shorter than the evolutionary one. All BH LMXBs with known $P_{\rm orb}$ are transients and do not have $P_{\rm orb}$ as short as NS LMXBs (none is below the period gap).

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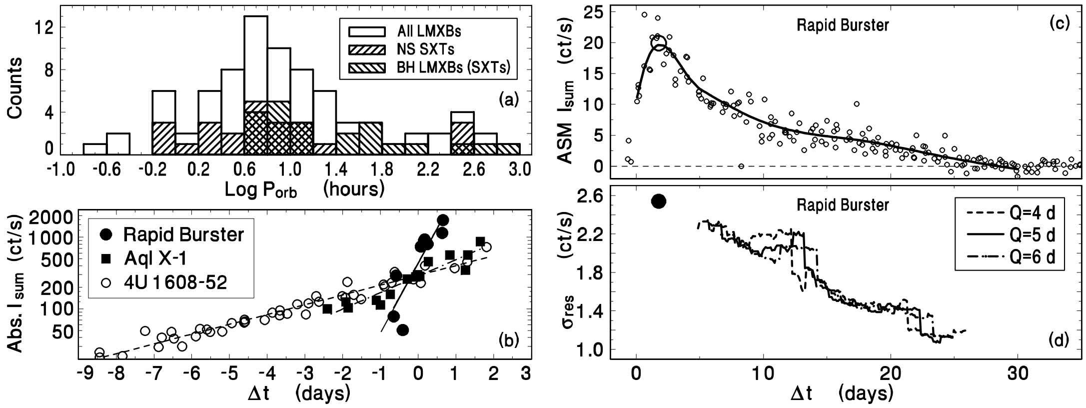

Fig. 1 **(a)** The statistical distribution of $P_{\rm orb}$ of LMXBs. **(b)** Rising branches of outbursts in NS SXTs (*ASM/RXTE* 1.5–12 keV data). The count-rates were re-calculated for the distance of the object and corrected for the interstellar extinction according to Liu et al. (2007). Several outbursts with the different peak luminosity were merged for each SXT. **(c)** Merged *ASM/RXTE* light curves of a group of six intense outbursts without type II bursts in the Rapid Burster, folded along the rising branch and smoothed by the code HEC13 (Prof. Harmanec; Vondrák 1969, 1977). A large open circle represents the mean $I_{\rm sum}$ of the fitted maxima. **(d)** Residuals $\sigma_{\rm res}$ of the fit in panel c smoothed by two-sided moving averages with various semi-intervals Q of the filter.

3 THE PROPERTIES OF OUTBURSTS IN SXTS

3.1 Rising Branches

Comparison of the rising branches of outbursts of several NS SXTs (Fig. 1b) shows that each of these systems preserves its own rise time scale $\tau_{\rm r}$, independent on the peak luminosity of its outburst. According to Narayan (1997), the central region of the disk in SXT is truncated and replaced by an extremely hot, optically thin advection-dominated accretion flow (ADAF) in quiescence. This ADAF is surrounded by a disk on the cold branch of the S-curve. The model of Dubus et al. (2001) shows that a smaller radius of ADAF yields a faster outburst rise. No second, slower phase of the rise is apparent in the outbursts of the Rapid Burster, which can suggest its small disk and hence $P_{\rm orb}$ shorter than in Aql X-1 and 4U 1608–52 and/or outside-in outburst. Each of these three SXTs thus possesses a specific size of optically thin ADAF that is reproduced for the individual quiescent intervals.

3.2 Decaying Branches

The model by King & Ritter (1998) explains the outburst profile of SXT in terms of irradiation of the disk by X-rays from the close vicinity of the mass-accreting object. In case of strong irradiation, the whole disk is kept in the hot state and no cooling front can form. The decay of the light curve is exponential. A linear decay is predicted to occur in a disk, whose inner region is kept in the hot state by irradiation while the outer parts are not. Propagation of the cooling front is controlled by irradiation in this case. A linear decay thus occurs when irradiation is reduced (e.g. in the late phase of outburst) or if the disk is large. The behavior of 4U 1608–52 supports this model; only during its brightest outbursts is the luminosity high enough for the disk to be ionized out to its outer rim by X-rays (Šimon 2004). However, the situation is even more complicated since the disk profile changes from concave to convex by irradiation (Dubus et al. 1999). A vertically extended irradiating source and/or a warped disk are thus needed. Alternatively, a larger disk flaring can be caused by the turbulence driven by magnetotoroidal instability (Begelman & Pringle 2007); in such case, the disk remains concave even when subject to irradiation. Irradiation of the disk is also observed to evolve during outburst, being less stable in the early phase (Fig. 1d). In some cases, like the intense outburst in 4U 1608–52 with the maximum in JD 2453460, a fast decay occurs in the initial phase of outburst in spite of the 1.5–12 keV intensity $I_{\rm sum}$ (measured by *ASM/RXTE*) high enough to keep the

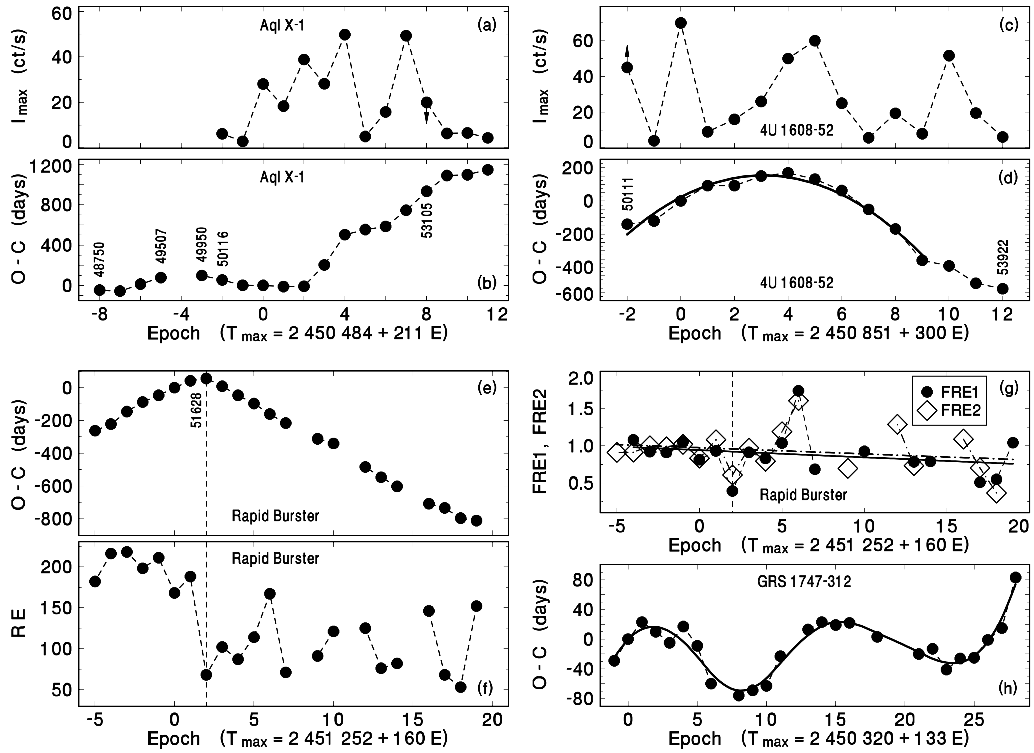

Fig. 2 **(a, b, c, d)** O–C diagrams for the moments of the outburst maxima and the profile of $I_{\max}$ of outburst in Aql X-1 and 4U 1608–52. Consecutive events (i.e. intervals without missing outbursts due to gaps in the data) are connected by lines. The Julian Dates (JD–2400000) are labeled for some points. A parabolic fit is shown for a part of the O–C curve in 4U 1608–52. **(e)** O–C diagram for outbursts in the Rapid Burster. **(f)** Variations of RE. **(g)** Evolution of $FRE1$ and $FRE2$ ($FRE1 = RE/\Delta t(E_i - E_{i-1})$, $FRE2 = RE/\Delta t(E_{i+1} - E_i)$); E_{i-1} and E_{i+1} refer to the preceding and following outburst, respectively. A vertical line at $E = 2$ denotes the moment of a large change of $T_{\rm C}$. Solid and dot-dashed straight lines represent the linear fits to $FRE1$ and $FRE2$, respectively. **(h)** O–C diagram for outbursts in GRS 1747–312. *ASM/RXTE* data were used in all cases.

whole disk in the hot state by irradiation; this implies that the irradiating source is not yet fully developed. Also a shielding of the outer disk region by a disk structure (spiral arms, warps (Truss et al. 2002)) may play a role. This is supported by the fact that the intensity, at which the transition from an exponential to a linear decay occurs in 4U 1608–52, differs from outburst to outburst (Šimon 2004).

The outburst decay rate depends on the viscosity near the edge of the outer radius kept in the hot state (King & Ritter 1998); mutual similarity of the individual decays thus implies that the viscosity achieves quite similar values for the individual events in a given SXT. The profiles and slopes of the final, mostly linear parts of decays in 4U 1608–52 and Aql X-1 are quite similar (Šimon 2002, 2004), and since $P_{\rm orb}$, and hence the disk radius is only slightly larger in Aql X-1 than in 4U 1608–52, this implies a similar value of viscosity in these two SXTs.

Peak absolute V band magnitudes of outbursts in 4U 1608–52 and Aql X-1 are comparable to dwarf novae (DNe) with long $P_{\rm orb}$ (GK Per, DX And), which allows one to infer that the disk in SXT radiates not only due to reprocessing off X-rays, but that viscous heating represents an important contribution to the optical luminosity at least in some SXTs.

An exponential decay of outbursts in the Rapid Burster (Fig. 1c) which displayed strong persistent emission without type II bursts (Guerriero et al. 1999) can be explained by irradiation of the disk by X-rays strong enough to ionize all of the disk out to its outer edge without self-shadowing, using the models by

King & Ritter (1998) and Truss et al. (2002). In this case, the parameters of irradiation (i.e. dimensions and luminosity of the irradiating body, disk profile) must reproduce with a relatively high degree of consistency for the individual outbursts. We find that the parameter C of irradiation of the disk (introduced in the model by Dubus et al. 2001) gradually decreases with the progress of outburst. $\dot{m}_{\rm C}$ attains the most divergent values in the phase when it reaches its peak value; the amplitude of its fluctuations gradually decreases later on. The feature 10–13 days after the onset of outburst can be interpreted as the spiral arms which begin to reach to the disk center, using the model by Truss et al. 2002. Large and rapid change of the profile of subsequent 12 outbursts can be explained by a change of the conditions for the disk irradiation.

The LMXB with an ultra-short $P_{\rm orb} = 50$ min (Walter et al. 1982) 4U 1915–05 can be considered as an extreme case of SXT, with the disk near the limit between thermally stable and unstable state. It displays low-amplitude, rapidly recurring outbursts with a decay time scale close to the viscous one. It appears to be an analogy with Z Cam DNe in intervals of their nearly critical $\dot{m}_{\rm tr}$ (Šimon 2005).

3.3 Evolution of Activity of SXTs

Analysis of very densely covered light curves from the X-ray monitor *ASM/RXTE* (1.5–12 keV) reveals that the variations of the recurrence time of outbursts $T_{\rm C}$ in SXTs are large, but generally not chaotic, and long-term trends can be clearly resolved (e.g. Šimon 2002, 2004, Fig. 2bdeh). Individual outbursts in a given SXT thus depend on each other. $T_{\rm C}$ shows large jumps and/or cyclic variations, which is not explicable by the evolutionary processes in the system. The behavior of $T_{\rm C}$ in SXTs is quite similar to that in DNe (e.g. Vogt 1980; Šimon 2000). The mean $T_{\rm C}$ in SXTs analyzed here is comparable to those in DNe with long $P_{\rm orb}$, like CH UMa and GK Per.

Large variations of the peak intensity of outburst $I_{\rm max}$ or the relative energy of outburst RE (profile of the light curve integrated over outburst) (Fig. 2acf) can be explained if the amount of mass accreted largely varies for the individual outbursts in a given SXT, since a lower $I_{\rm max}$ is not caused by a higher absorption of their X-ray emission (Šimon 2002, 2004). The fact that $T_{\rm C}$ evolves more gradually than $I_{\rm max}$ can be explained if the outburst is triggered in the inner edge of the disk, i.e. where the disk is in contact with ADAF in quiescence. We have shown in Section 3.1 that the radius of ADAF is reproduced well in a given SXT. The critical surface density, necessary to brought the disk annulus to the hot state, increases with the distance from the disk center. Each outburst in a given system thus starts in roughly the same radial distance. Provided that $\dot{m}_{\rm tr}$ remains relatively unchanged, we obtain $T_{\rm C}$ without large, rapid fluctuations. All this can explain why the length of $T_{\rm C}$ is more stable than $I_{\rm max}$; the outburst propagates inside-out, and hence it may not reach the outer disk rim. The outer disk region is brought to the hot state only in the rare, most intense outbursts. The statistical distribution of $I_{\rm max}$ is highly asymmetrical in both 4U 1608–52 and Aql X-1, with the faintest outbursts being most abundant. This supports our interpretation that the outbursts are triggered near the ADAF region and propagate outward in the disk.

Strong evidence that the disk is not considerably depleted in outburst can be found in 4U 1608–52, where a gradual accumulation of matter in the outer disk region plays a large role (Šimon 2004).

We argue that a change of $T_{\rm C}$ in the Rapid Burster (Fig. 2e, see also Masetti 2002) is not caused by the variations of $\dot{m}_{\rm tr}$. The reason is that the evolution of $FRE1$ and $FRE2$ (Fig. 2g) suggests that the amount of matter accreted during outburst is dependent on both the previous and following cycle-length and, on average, remains the same in spite of a considerable decrease of $T_{\rm C}$ (i.e. more frequently recurring outbursts occur in a lighter disk). Increase of the disk viscosity thus appears to be a viable explanation. The mean $T_{\rm C}$ of 133 days of GRS 1747–312 displays a cyclic modulation with the cycle-length of $\sim$5 years (Fig. 2h). This may suggest a cycle of stellar activity of the donor. $P_{\rm orb} = 12.360$ hr (in't Zand et al. 2000) suggests an evolved late-type donor which is expected to possess outer convective zone and hence cycles of activity.

3.4 Echo Outbursts

The so-called echo outbursts are brightenings which were observed on the decaying branch of outbursts or during high/low state transition of some LMXBs (e.g. KS 1731–260 (Fig. 3)) and DNe (e.g. WZ Sge (Patterson et al. 2002)).

Let us look at KS 1731–260 in more detail because it can serve as an example (Fig. 3). It was classified as an On/Off transient which stayed in the high state for several years (King 2006). Its transition from

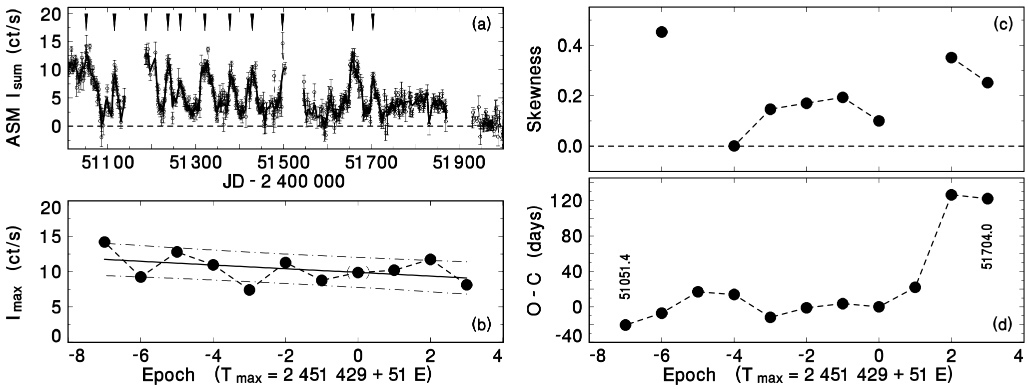

Fig. 3 Evolution of the echo outbursts in KS 1731–260. **(a)** A part of the *ASM/RXTE* light curve fitted by HEC13 (smooth solid line). **(b)** Variations of $I_{\max}$ and their linear fit. **(c)** Skewness of the outburst light curve. **(c)** O–C diagram for T_{C} of the echo outbursts. Only the clearly defined outbursts with the maximum of the fitted curve $I_{\mathrm{sum}} > 7$ ct s^{-1} were considered.

(quasi)persistent X-ray source to quiescence (or even hibernation) then went through a series of outbursts similar to those in SXTs. These echo outbursts of KS 1731–260 can be interpreted as a decrease of $\dot{m}_{\,\mathrm{tr}}$ which lead to a transition from a thermally stable to unstable disk. The peak intensity of the echo outbursts lies on an extrapolation of a gradually decaying level of emission prior to the onset of instability. Skewness > 0 (Fig. 3c) suggests that the echo outbursts possess a steeper rise than decay. This steep rising branch implies that the heating front starts in the outer disk region (outside-in type of outburst). The disk did not get into real low state between most echo outbursts of KS 1731–260 because $I_{\,\mathrm{sum}}$ was clearly above the quiescent value; a series of heating and cooling fronts thus formed. Evolution of the X-ray hardness ratios $HR1 = I(3-5\,\mathrm{keV})/I(1.5-3\,\mathrm{keV})$ and $HR2 = I(5-12\,\mathrm{keV})/I(3-5\,\mathrm{keV})$ with I_{sum} shows that the X-ray spectrum in outburst maximum is consistent with that in the high state. The relatively smooth profile of the O–C curve (Fig. 3d) suggests that the individual echo outbursts are dependent on each other. The state of long-term activity of "classical" SXTs is not the same as in KS 1731–260. Especially well observed NS SXTs (e.g. Aql X-1, 4U 1608–52) display outbursting activity in which the disk alternates between cold and hot state. On the contrary, the disk in KS 1731–260 was depleted during a short time and the system may be in the hibernation state now.

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DISCUSSION

WOLFGANG KUNDT: Please remind me of your detection criteria for echo outbursts; how long are the echo delay times?

VOJTĚCH ŠIMON: Echo outbursts are events which occur on the declining branch of the main outburst, or shortly after its end. Their recurrence time is at most a few percent of that of the main outbursts, that is much shorter. Also the duration of the whole series of echo outbursts is much shorter than the time interval to the next main outburst.