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# The X-Ray Binary KS 1731–260: Possible Analogy with Her X-1

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**Abstract**

The X-ray binary with the neutron star (NS), KS 1731–260, displays superorbital cycle similar to that in Her X-1. The accretion disk had the memory of the cycle-length even when this modulation sometimes disappeared in the main outburst of KS 1731–260, and during anomalous low state in Her X-1. The disk still existed during such seasons. Although irradiation of the disk by X-rays is a viable explanation for the disk precession and warping (see model of Foulkes et al.), the mechanisms which give rise to the observed X-ray modulation are quite different for each of these systems. Variable absorption can explain this cycle only in Her X-1. We propose a variable mass accretion rate onto the NS in KS 1731–260 due to a highly variable impact of the inflowing mass stream with the changing phase of the cycle.

**Keywords:** radiation mechanisms - accretion, accretion disks - x-rays: binaries - optical - X-rays.

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## 1 Introduction

KS 1731–260 (e.g. [2, 32]) and Her X-1 (e.g. [10]) are mass exchanging X-ray binary systems, with the neutron star (NS) accreting matter from a low (or medium)-mass companion. They can be considered specific type of transient systems as regards their activity (On/Off transients in the notation of [13] (rapid rise, very long (years) lasting state of activity, rapid return to the inactive state)). Their active X-ray states were accompanied by intense brightenings by more than a magnitude in the optical [12] and near infrared bands [21, 32].

Both these systems display cyclic modulation of X-ray intensity during the active state (Her X-1: the cycle-length $P_{\rm C} \approx 35$ d [28], KS 1731–260 $P_{\rm C} \approx 38$ d [22]). This modulation is superorbital (about 20 times longer than the orbital period $P_{\rm orb}$) in Her X-1 because its $P_{\rm orb}$ is only 1.7 d [28]. Since the observations of KS 1731–260 in quiescence showed that the donor is of type G5V (with a contribution of a synchrotron jet) [32], it is possible that the cycle is superorbital, too, if this star fills its Roche lobe.

## 2 Observations

The data from ASM/*RXTE* [15] (one-day means) were used. They contain the intensities $I_{\rm sum}$ (1.5–12 keV) and $I_{\rm A}$ (1.5–3 keV), $I_{\rm B}$ (3–5 keV), $I_{\rm C}$ (5–12 keV). The hardness ratios are $HR1 = I_{\rm B}/I_{\rm A}$ and $HR2 = I_{\rm C}/I_{\rm B}$. The optical data of Her X-1 come from the AAVSO International database (Massachusetts, USA) [11].

## 3 Active State in KS 1731–260

In KS 1731–260, the X-ray active state with a complicated evolution lasted for about 12.5 years [4]. After return to quiescence, the luminosity is very similar to that of the other quiescent NS systems [31]. The end of the active state was accompanied by a decrease of brightness by about 1.7 mag($H$) in the infrared [21, 32].

ASM/*RXTE* monitored part of the active state. It consisted of two segments of a largely different activity. In the scenario of [24] using the model of [6], the whole disk was thermally stable in the hot (ionized) state during the main outburst. The rapid end of the main outburst was followed by a series of the echo outbursts, ascribed to a thermally unstable disk with a series of recurrently propagating cooling and heating fronts.

The X-ray light curve observed by ASM/*RXTE* is shown in Fig. 1a. Moving averages (MA) of $I_{\rm sum}$ with the filter half-width $Q = 5$ d enhance the visibility of the modulation on a timescale of days. To determine the long-term evolution of $I_{\rm sum}$ averaged over these fluctuations, the data were fitted with the code HEC13. It was written by Prof. P. Harmanec using the method of [30]. The changes of $I_{\rm sum}$ are not accompanied by the variation of $HR1$ in the sense expected if absorption is the cause of the modulation (using the coefficients of [18]) (Fig. 1b). The same is true for $HR2$.

Search for the cycle-length in MA from Fig. 1a was carried out with the weighted wavelet Z-transform (WWZ) developed by [7]. This method enables one to determine the period and amplitude of unevenly sampled time series. WWZ indicates whether or not there is a periodic fluctuation at a given time at a given frequency $f$ (Fig. 2a). A similar result was obtained for the one-day means of $I_{\rm sum}$. It emerges that neither the period of the modulation, $P_{\rm C}$, nor its amplitude are stable. $P_{\rm C}$ is not conclusively detected in some segments. This is caused by a real, abrupt change of the light curve.

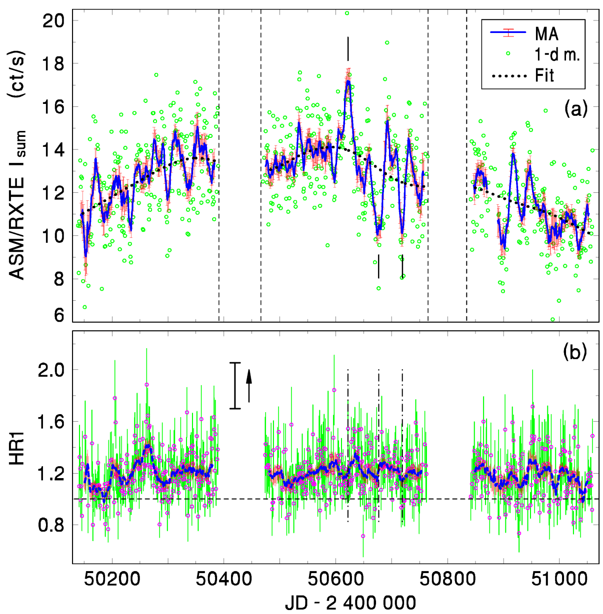


**Figure 1: (a)** X-ray light curve of KS 1731–260 during the main outburst. MA of $I_{\rm sum}$ ($Q = 5$ d) enhance the visibility of the modulation. The smooth curve shows the main trend (the HEC13 fit). The time interval around the conjunction with the Sun is marked. **(b)** Time variation of $HR1$. The smooth line represents MA for $Q = 8$ d. The errors of MA are the standard errors. The big error bar and arrow in panel **b** mark the influence of absorption. Three prominent extrema of $I_{\rm sum}$ and their $HR1$ are marked. See Sect. 3 for details. Adapted from [25].

Fig. 2b shows the best $P_{\rm C}$, determined from $f$ that has the biggest value of WWZ at a given time (only the segments in which the amplitude is larger than 50 percent of its peak value). See [25] for details. The recurrence time $T_{\rm C}$ of the echo outbursts is about 51 days [24], which is quite different from $P_{\rm C}$ in the main outburst (see also [22]).

Absorption of X-rays would influence mostly $I_{\rm A}$. However, the variations of soft X-ray intensity during the cycle suggest intrinsic changes of emission at unchanged absorption (Fig. 1b).

The echo outbursts after the main outbursts in some transients are helpful in investigating the nature of the above-mentioned cycle in KS 1731–260. The recurrence time $T_{\rm C}$ of the echo outbursts is significantly longer for the systems with longer $P_{\rm orb}$ [24]. In this regard, we present arguments in favor of the superorbital nature of the cycle in the main outburst of KS 1731–260. If $P_{\rm C}$ of 38 d were close to $P_{\rm orb}$, the expected $T_{\rm C}$ of the echo outbursts would be at least 800 days, much longer than observed.

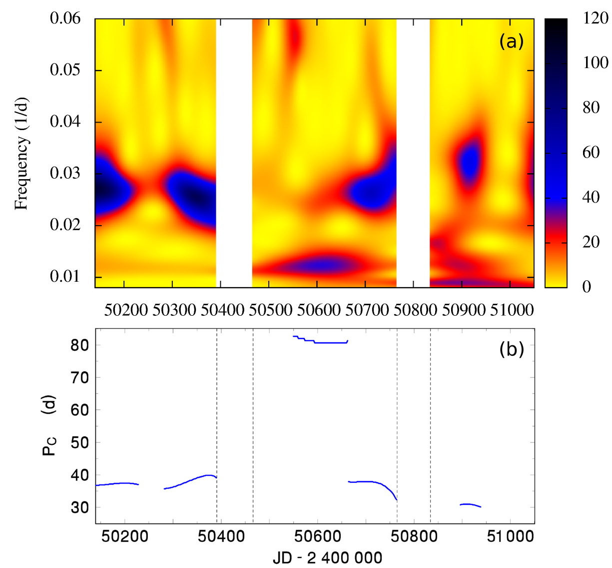


**Figure 2: (a)** WWZ-transform of the moving averages of KS 1731–260 from Fig. 1a. **(b)** The best cycle-length. See Sect. 3 for details. Adapted from [25].

## 4 Activity in Her X-1

The X-ray light curve of Her X-1 displays only two segments (discrete spikes) of the On state (Main-On and Short-On) during the 35 d cycle (e.g. [28, 14]). On and Off-states do not form a clear profile of the long-term light curve in the ASM/*RXTE* data; only two anomalous low states ALS1 and ALS2 in which $I_{\rm sum}$ was below the detection limit can be resolved. Instead of the light curve, the activity was therefore studied using the fluence of each Main-On spike (Fig. 3a). This fluence was determined by an integration of $I_{\rm sum}$ over the profile of the Main-On state. The scatter of fluences of the individual spikes is real. Their time evolution is emphasized by the HEC13 fits. They reveal a cycle of about 400 d.

Evolution the 35 d cycle, measured by the turn-on times of the Main-On state, is correlated with that of the spin period of the NS. This suggests the evolution of the transfer of angular momentum from the disk to the NS [27]. The 35 d cycle-length is always unstable, but the largest changes coincide with ALS. ALS thus represents an episode of the largest change of the mass flow through the disk onto the NS. The disk remembers the conditions for the 35 d cycle-length and its phase (mainly after ALS2).

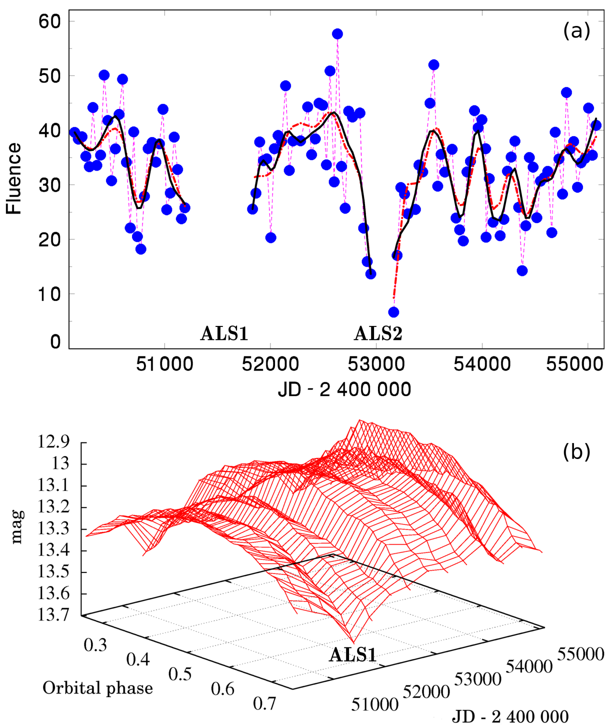


**Figure 3:** **(a)** Time evolution of fluence of Main-On states (1.5–12 keV) in Her X-1. Each episode of this state represents a point in the curve. The smooth lines represent the fits to the time evolution. **(b)** Smoothed evolution of the optical orbital modulation of Her X-1 with time. See Sect. 4 for details.

The profile of the unique optical emission plays an important role in distinguishing between the character of the active and inactive states in Her X-1. Dominant part of the optical emission in the active state is due to reprocessing off X-rays from the close vicinity of the NS on the part of the photosphere of the donor facing the NS (e.g. [10]). Occasional inactive states in which the orbital modulation remained flat and the optical emission faint occurred only before the X-ray astronomy era (e.g. [12]). They were caused by temporary decreases of this irradiation. A heavy smoothing of the AAVSO optical data enabled to study the time evolution of the orbital modulation, hence of the X-ray irradiation of the donor (Fig. 3b). This revealed a relation between the optical and X-ray long-term activity. In spite of a decrease of the optical brightness accompanying the fall of X-ray flux in ALS1, the X-ray irradiation remained. This implies that accretion continued even during ALS1. This event was therefore not a real low state like those in the pre-X-ray astronomy era.

A similar situation was the ALS in 1983 when the optical modulation of Her X-1 remained comparable to that in the active state [5]. However, the observations by the *ASTRON* satellite revealed very large differences between the X-ray spectra obtained in this ALS and after recovery from this low state (1984) [26]. Intense cyclotron emission of the NS dominated during normal Main-On state of the 35 d cycle (Aug 25, 1984). On the contrary, the X-ray spectrum obtained in ALS in the phase when Main-On state was expected (June 30, 1983) showed a combination of a faint cyclotron emission of the NS and reflection of the donor. Both the orbital modulation in the optical band and the reflection of the donor in the X-ray band confirmed that the mass accretion continued during ALS.

ALS1 in Fig. 3a appears to be extreme in the sense that both the change of the 35 d cycle of the disk and the increase of the spin period of the NS had the largest amplitude among the episodes of ALS [27]. The decrease of the optical brightness in ALS1 (Fig. 3b) then suggests that these changes of the disk were also accompanied by a decrease of the X-ray irradiation of the donor.

## 5 Conclusions

The modulation of X-ray emission in KS 1731–260 was first attributed to the precession of the accretion disk by [22]. Its $P_{\mathrm{C}} \approx 38$ d in the main outburst is quite different from $T_{\mathrm{C}} \approx 51$ d of the echo outbursts. The series of the echo outbursts in KS 1731–260 [24] can be used as an independent method for determining its $P_{\mathrm{orb}}$ to be about $0.5 - 1$ d [24]. Since the length of $P_{\mathrm{orb}}$ is by more than an order of magnitude shorter than $P_{\mathrm{C}}$, KS 1731–260 became a new member of the family of X-ray binary systems with superorbital cycles. The superorbital cycle of KS 1731–260 cannot be caused by transitions of the disk between the hot and the cool state because it occurred only during the phase of the hot (ionized) state of the disk (see also [25]).

The disk had the memory of the cycle as regards the length of $P_{\mathrm{C}}$ in KS 1731–260 even when this modulation sometimes disappeared in the main outburst, and in Her X-1 during ALS. Nevertheless, the disk still existed even during these phases, which is suggested by the intense X-ray emission in KS 1731–260 and the reprocessing off X-rays in the optical band in Her X-1.

Intense irradiation of the disk by X-rays is a viable explanation for the disk precession and warping (see models of [8, 9]). Indeed, KS 1731–260 and Her X-1 are strong emitters ($L_{\mathrm{X}} \approx 1.8 \times 10^{37}$ erg s$^{-1}$ in the main outburst of KS 1731–260 [20], $L_{\mathrm{X}} \approx 2 \times 10^{37}$ erg s$^{-1}$ in the Main-On state of Her X-1 [17]). This is about 0.1 of the Eddington luminosity. However, it is necessary to find how this precession gives rise to the modulation of the observed X-ray intensity. In Her X-1, absorption causes X-ray variations during the cycle [23]. However, this explanation is not applicable to KS 1731–260.

We propose an alternative explanation for the modulation in KS 1731–260. The models of [8, 9] show that the stream of matter inflowing from the donor reaches quite different impact regions of the tilted and warped disk during the cycle. This impact can occur deep in the inner disk region in some phases. This therefore affects the mass flow in the inner disk during the individual phases. In this scenario, the true cycle-length can be twice as long if the profile is double-wave. The almost constant $HR1$ and $HR2$ during the cycle can be explained if the spectral components [4] and their intensities vary with a variable mass accretion rate onto the NS. The number of mechanisms for the modulation during superorbital cycle therefore increases in this family of systems.

In KS 1731–260, the atoll shifts on a timescale of less than a day [3] are superimposed on the superorbital cycle. According to [1], atoll type shifts are caused by variations of the mass accretion rate onto the NS. This suggests that the accretion is due to the contributions of various simultaneous flows of matter.

Magnetic flux density $B$ of the NS is important for the emission mechanism in the X-ray band. Is there any relation between this mechanism and the superorbital cycle? Her X-1 contains a pulsar with the spin period of 1.24 s (0.806 Hz) [28] and $B \approx 5 \times 10^{12}$ Gauss [29]. It produces cyclotron emission (e.g. [16]). On the other hand, KS 1731–260 is a millisecond pulsar with the spin period of 524 kHz [19]. In the main outburst, its emission is a combination of an optically thick Comptonization component and a blackbody component [20]. This suggests $B$ of the NS much smaller than in Her X-1. All this implies that the superorbital cycle can operate even for such largely different mechanisms of X-ray emission, hence for the largely different $B$ and the accretion flows near the NS.

## Acknowledgement

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