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LOW-MASS BINARY X-RAY SOURCES: MONITORING WITH VARIOUS SATELLITES

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Abstract. We show the importance of observing low-mass binary (LMXB) X-ray sources with the X-ray monitors onboard satellites. This enables us to study the physical processes governing the long-term activity of LMXBs. They are excellent targets for monitoring because of their strong activity. We recall that various physical processes operating in LMXBs produce specific large-amplitude variations of X-ray luminosity which can be investigated even in a single-band X-ray light curve as often provided by the monitors. We also emphasize the role of the spectral region of the X-ray monitor. Choosing the spectral region often strongly influences the profile of the observed intensity curve because different emission components may dominate in different X-ray energy ranges. We show several examples of LMXBs which undergo various types of unpredictable activity (e.g. outbursts, superorbital cycles).

Keywords: Radiation mechanisms, accretion, accretion disks, X-rays: binaries, X-ray monitors, X-ray detectors.

1. Introduction

Low-mass X-ray binaries (LMXBs) are systems in which matter flows from a companion star, the so-called donor (often a low-mass, main-sequence star), onto a compact object which acts as an accretor. This object is either a neutron star (NS) or a black hole (BH). Release of gravitational energy during accretion of matter from the donor onto the compact object is often the dominant energy source of a LMXB. In this system, the accretion occurs in the disk embedding the compact object. A review can be found e.g. in [1].

Most X-rays come from the close vicinity of the compact object in a LMXB. The inner disk region emits thermal radiation, which contributes to the soft X-ray emission output (with energies E up to several keV). Comptonizing cloud around the compact object produces an emission via inverse Compton scattering. It is dominant especially in hard X-rays (with E even larger than 10 keV). These systems often display strong activity on various timescales, from a very small fraction of a second to many years (e.g. [1]).

2. The importance of monitoring

The activity of LMXBs in the X-ray band on the timescales of years and decades is little explored, also because of the necessity to conduct monitoring in the X-ray band. We discuss the big role of monitors of X-ray emission in studying the physical processes operating in LMXBs.

LMXBs are excellent targets for monitoring. Systems of this type display various kinds of long-term activity (e.g. [2]). We stress the importance of long-term coverage in the X-ray band. The reason is that occasional pointing in any spectral band is not enough, because many pieces of information on the time evolution of the studied object are lost by this strategy. In addition, time allocation has to be justified, because a search for unexpected behavior of the object is usually not approved. Moreover, determining a comprehensive picture of the processes operating in a given LMXB (or a group of such systems) requires an analysis of an ensemble of events even in the same system. We will discuss the activity of LMXBs in various X-ray bands and how monitoring helps.

So-called LMXB transients are those for which the intensity of their emission increases even by several orders of magnitude from time to time. Wide-field monitoring of the sky is necessary because most transients are discovered only by the first detection of their outburst. Such outbursts of LMXBs are unpredictable. Only the mean recurrence time (cycle-length) $T_{\rm C}$ of these events can be determined. Of course, a long (years or, preferably, decades) series of observations is necessary for this basic determination. This activity is interpreted by thermal-viscous instability of the accretion disk [3]. In this case, the time-averaged mass transfer rate from the donor to the compact accretor lies between certain limits. The mass accumulates in the outer regions of the disk during quiescence. When some critical mass density of the disk is reached, strong accretion of matter from the disk onto the central compact object triggers the outburst, hence a fast increase of X-ray intensity [3].

Some other LMXBs are (quasi)persistent X-ray sources, which means that they are detectable repeatedly, possibly always. Some of them can display transitions between the high and low states of X-ray intensity, which is probably caused by a transient decrease of the mass transfer rate. These transitions are usually fast (several days) and unpredictable. Even when these LMXBs reside in the high state (i.e. in a state of high intensity), their X-ray intensity is not quite constant; it often displays significant fluctuations. They may also display cyclic (superorbital) changes of luminosity on a timescale of weeks and months, interpreted in terms of precession of the accretion disk (e.g. [4]).

2.1. Remarkable X-ray monitors

The All Sky Monitor (ASM) operated onboard the NASA *Rossi X-ray Timing Explorer* (*RXTE*) [5] (`http://xte.mit.edu/`) between 1996 and 2012. This monitor consisted of three wide-angle shadow cameras equipped with proportional counters, each with 6×90 degrees of field of view. The collecting area was $90\,\mathrm{cm}^2$. The detector was a position-sensitive Xenon proportional counter. Spatial resolution was 3×15 arcmin. Time resolution was 80 percent of the sky every 90 min. The sensitivity was about 13 mCrab for the one-day means of observations. Such averaging of data is often used for analyses of the observations from this instrument to increase the signal to noise ratio. ASM/*RXTE* was an excellent monitor for soft X-rays. The data contain the sum band intensities I_{sum} in the 1.5–12 keV band and the intensities in three sub-bands: I_{A} (1.5–3 keV), I_{B} (3–5 keV), I_{C} (5–12 keV). This enables us to calculate the hardness ratios $HR1 = I_{\mathrm{B}}/I_{\mathrm{A}}$ and $HR2 = I_{\mathrm{C}}/I_{\mathrm{B}}$.

The Burst Alert Telescope (BAT) onboard the NASA satellite *Swift* has been operating since 2004 [6, 7]. It is equipped with a coded mask. Its detecting area is $5200\,\mathrm{cm}^2$. The field of view is 1.4 sr (partially-coded). This is a monitor for very hard X-rays. Its energy range is 15–150 keV. Nevertheless, the 15–50 keV band is used for monitoring X-ray sources. It is not divided into sub-bands.

2.2. Data from X-ray monitors

What can we expect from data from X-ray monitors? When a LMXB is in its high state of activity (e.g. in outburst), the X-ray spectrum usually displays the biggest intensity in the soft X-ray band (E about 2 keV) (e.g. [8]). The intensity decreases steeply with growing E. It is therefore desirable to construct monitors observing the soft X-ray band. The monitors often work with a single band (typically in soft X-rays, with E of a few keV); this is suitable for utilizing the spectral band in which the emission of LMXBs is most intense during the states when they can be detected by these instruments. The famous ASM/*RXTE* monitor even provided observations in three bands (Sect. 2.1). Dividing the observed spectral region into several bands (e.g. those used in ASM/*RXTE*) or simultaneous usage of various monitors (e.g. ASM/*RXTE* along with BAT/*Swift*) helps to distinguish between various processes and spectral components influencing the X-ray luminosity. In addition, absorption of X-rays can be measured in the ASM/*RXTE* data by simultaneous use of the intensities in band A, band B, and band C. Absorption is predicted to influence mostly the softest ASM band ([9]).

Various physical processes operating in LMXBs produce specific large-amplitude variations of X-ray luminosity on a timescale of days, weeks, even years and decades (e.g. [2]). The characteristic features of such activity (e.g. outbursts, high/low state transitions, superorbital cycles) can be investigated even in a single-band X-ray light curve of a LMXB. Even some model predictions of the features of the long-term activity are already available. For example, the properties of the basic outburst light curves in soft X-rays, T_{C}, and the dependence of the outburst profile on irradiation of the disk by X-rays from the vicinity of the accretor were modeled by [3].

2.2.1. Aql X-1

The soft X-ray transient Aql X-1 spends most time in quiescence, in which its intensity is too low to be detected by the monitors. From time to time (after roughly 200 days), this system switches to an outburst, during which it can rapidly become a bright X-ray source for several weeks. Part of its ASM/*RXTE* light curve is displayed in Fig. 1a. Simultaneous evolution of its intensity in the BAT/*Swift* data (Fig. 1b) shows that most outbursts are detectable also in the very hard X-ray band. Fig. 1ab is thus an example of the fact that both the profile and the intensity of a given outburst in the same LMXB sometimes differ very considerably for the spectral region used by the monitor. It is therefore risky to compare the profiles of the outbursts obtained by various monitors. This strengthens the importance of constructing a monitor and its satellite which can operate on the orbit as long as possible to provide a reasonable ensemble of events (e.g. outbursts) which will enable an analysis.

The outbursts in Aql X-1 (and in similar soft X-ray transients) are discrete and separated from each other. Their peaks can often be resolved easily. It is thus possible to apply the method of O–C residuals (‘O’ simply stands for observed and ‘C’ for calculated) to T_{C} of the outbursts. The O–C method was successfully applied in analyzing outbursts, e.g. by [10, 11]. It enables us not only to determine T_{C}, but also to analyze its variations. It works with the residuals from some reference period (i.e. with the deviations from a constant period). The O–C curve also enables us to assess the position of each outburst with respect to the O–C profile of the remaining outbursts. This method can work even if some outbursts are missing due to the gaps in the data, provided that the profile of the O–C curve is not too complicated. It is known that T_{C} of soft X-ray transients like Aql X-1 can vary by a large amount. Nevertheless, in many cases, the changes of T_{C} are not chaotic, and well-defined trends can be resolved in the O–C diagrams. The evolution of T_{C} of the outbursts in Aql X-1 is shown in Fig. 1c.

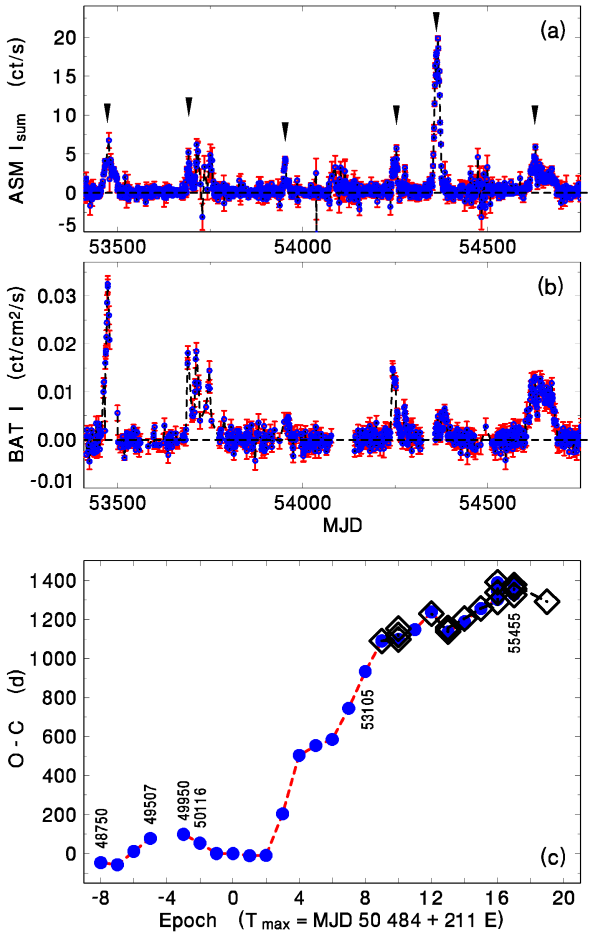

Figure 1. **a)** Part of the ASM/*RXTE* light curve of the soft X-ray transient Aql X-1. The outbursts are marked by arrows. **b)** Simultaneous evolution of its intensity in the BAT/*Swift* data. **c)** O–C diagram for the recurrence time T_C of the outbursts in Aql X-1. Diamonds represent the values determined from observations by BAT. Circles represent observations by other instruments (often using ASM/*RXTE*). See Sect. 2.2.1 for details. (This figure is available in color in electronic form.)

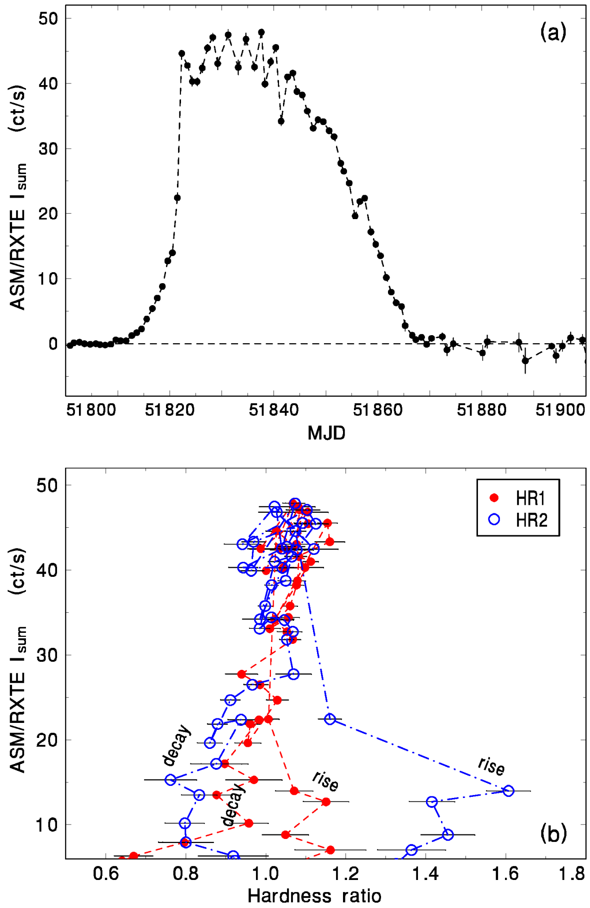

Figure 2. **a)** The profile of a bright outburst in Aql X-1 (ASM/*RXTE* sum band (1.5–12 keV) data). **b)** The dependence of HR1 and HR2 on I_{sum} of the outburst. The symbols are connected by lines to trace the evolution of the outburst. See Sect. 2.2.1 for details. Adapted from [11]. (This figure is available in color in electronic form.)

Since these outbursts are only cyclic, monitoring is necessary for detecting them, especially their steep rising branch.

Although the profiles, and hence the peaks, of a given outburst may differ for the ASM and BAT bands, this difference is much smaller than T_C. It thus does not influence the profile of the O–C curve significantly. However, some outbursts may be too faint in the BAT band, even when they can still be detected in the ASM band. When only the BAT observations are available now, some outbursts may escape detection (Fig. 1c).

An example of the profile of a bright outburst in Aql X-1, observed in the ASM/*RXTE* 1.5–12 keV band, is displayed in Fig. 2a. The evolution of hardness ratios $HR1$ and $HR2$ (defined in Sect. 2.1) with I_{sum} of this outburst shows a strong hysteresis (Fig. 2b). Both these ratios are considerably larger in the bottom half of the rising branch than during the decay from the outburst peak.

Aql X-1 can also serve as an example of the fact that the sensitivity of the monitors plays a big role in a study of the features of the light curves. For example, the X-ray data obtained in the 3–12 keV band by *Vela 5B* between years 1969 and 1976 were averaged into 10-day means [12]. Later, ASM/*RXTE* observing in the 1.5–12 keV band (similar to that of *Vela 5B*) between years 1996 and 2012 [5] was able to detect significantly fainter outbursts included in the activity of Aql X-1. Averaging the observations into one-day means was already sufficient. Including these minor outbursts which were resolved by ASM/*RXTE* was important for the correct assessment of the activity of this object (e.g. [11]) (see also Fig. 1a). This system also serves as clear evidence that the profile of the O–C curve is reliable only if the faint outbursts are also detected.

2.2.2. XTE J1701–462

A comparison of the profiles of the ASM/*RXTE* and BAT/*Swift* light curves of the very long outburst of

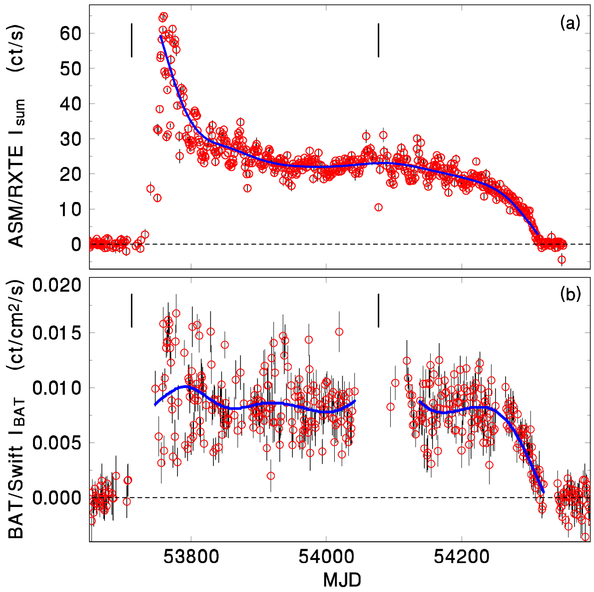

FIGURE 3. **a)** ASM/*RXTE* light curve of the very long outburst in XTE J1701–462 fitted with HEC13 running through the fluctuations. **b)** BAT/*Swift* light curve of the whole outburst fitted with HEC13 running through the fluctuations. Vertical lines denote the conjunction of the system with the Sun. See Sect. 2.2.2 for details. (This figure is available in color in electronic form.)

XTE J1701–462 shows striking differences (Figs. 3a and 3b). Both these light curves display a plateau in the middle phase of the outburst, but the transition to it differs. Although BAT did not map the time segment of the rising branch of the outburst, ASM observed a steep rise of intensity to a prominent initial peak of the outburst. Noticeable fluctuations on a timescale of several days (i.e. on a timescale much shorter that the duration of the whole outburst) were present in the ASM data in some phases (especially during the initial peak of the outburst). The whole part of the BAT light curve prior to the onset of the fast final decay of intensity displayed large-amplitude chaotic variations on a timescale shorter than in the ASM band. It required smoothing to distinguish the profile of the outburst. The data were therefore fitted with the HEC13 code, written by Prof. P. Harmanec. The code is based on the method of [13, 14], who improved the original method of Whittaker [15]. The resulting fit consists of the mean points, calculated to the individual observed points of the curve. The peak-to-peak amplitude of these fluctuations was significantly larger than the measurement error $u_{\rm BAT}$ of the individual daily means of intensity in the BAT band. Notice especially the very large decrease in the amplitude of the fluctuation near MJD 54 260, shortly before the onset of the steep final decline of the outburst. The fitting procedure of the BAT light curve was made with the same input values as for the ASM data (Fig. 3b).

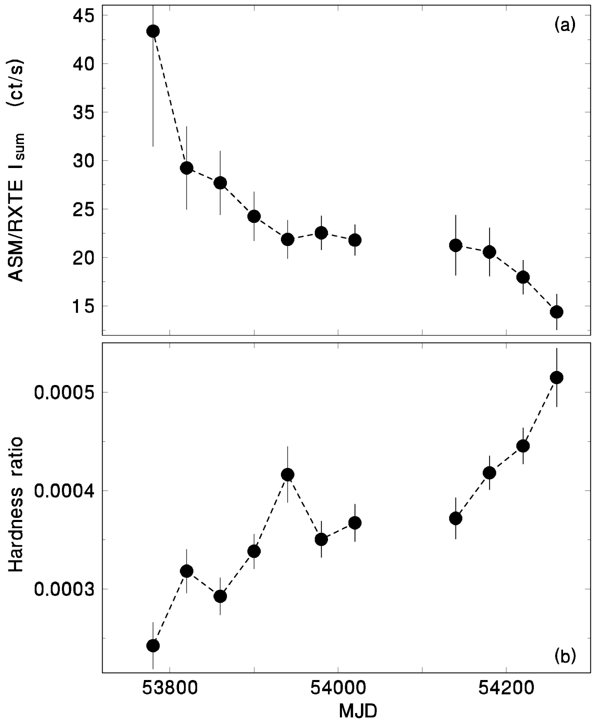

FIGURE 4. The relation of the time evolution of $I_{\rm sum}$ **(a)** and the hardness ratio $HR = I_{\rm BAT}/I_{\rm sum}$ **(b)** during the decline of the very long outburst in XTE J1701–462. HR and $I_{\rm sum}$ were determined for the data included in a segment of 40 days. The consecutive points are connected by a line. The standard errors of $I_{\rm sum}$ and HR are displayed. See Sect. 2.2.2 for details.

To investigate the time evolution of the hardness ratio $HR = I_{\rm BAT}/I_{\rm sum}$ ($I_{\rm BAT}$ being the intensity measured by BAT) during the decline of the outburst, it was necessary to overcome the problem of the large-amplitude fluctuations of the intensities in both these bands. Such strong fluctuations occurred especially in the profile of the BAT light curve. It was not possible to take the fluctuations in the one-day means of $I_{\rm BAT}$ as precisely coinciding with the measurements included in the one-day means of $I_{\rm sum}$. The problem was solved in the following way. Part of the outburst beginning in MJD 53 783 was divided into 11 bins. The width of each bin was 40 days. The resulting means of both $I_{\rm sum}$ and $I_{\rm BAT}$ along with their standard errors were determined for each bin. Only these means were used for the calculation of HR in each bin. The result is displayed in Fig. 4. Generally, the spectrum hardens with time during the outburst's decline, with the exception of a shallow dip centered on MJD 53 940. Moreover, the time evolution of HR displays a shorter plateau than the ASM light curve. This is because the increase of HR is slower than that of $I_{\rm sum}$ during the decline of $I_{\rm sum}$ from the initial peak and also during the final decay. In addition, a relation between $I_{\rm sum}$ and HR exists, with the steeper rise of HR in the upper half of the $I_{\rm sum}$ range. The initial peak in the $I_{\rm sum}$ light curve caused this steepening.

2.2.3. Several other examples

An outburst of the BH transient GX 339–4 was simultaneously monitored by ASM/*RXTE* and BAT/*Swift* [16]. This combination revealed very large differences between the profiles of the outburst in the soft and the very hard X-rays. Although the start of this outburst was almost simultaneous for both spectral bands, a state transition occurred close to the time of the peak luminosity. This resulted in a very fast decay of the BAT luminosity, while the decaying branch of the outburst was much less steep. Nevertheless, a re-brightening in the BAT light curve gave rise to the much longer total duration of the outburst in the BAT band than in the ASM band [16].

Cyg X-2 is a persistent X-ray source with a mass-accreting NS (e.g. [17]). It is known to display superorbital cycles observed by several satellites (*RXTE*, *Vela 5B*, *Ariel 5*) (e.g. [18, 19]). A complex evolution of the cycle-length (sometimes even multiperiodic cycles) was observed (e.g. [19]). The lengths range from about 40 d to 78 d. This behavior was interpreted by [19] as a complex warping shape of the accretion disk given by the position in the binary radius–precession frequency diagram of [20]. The amplitude of the cycle in the ASM/*RXTE* band is large; the intensity can decrease by about 50 percent. This cycle is thus easily detectable by various monitors and its complex evolution can be studied in long time segments. The variations of intensity were accompanied by changes of the hardness ratio, interpreted by variable obscuration of X-rays [19].

The long-term variations of X-ray intensity of the persistent X-ray source 4U 1820–30 display a large-amplitude superorbital cycle of about 176 days (e.g. [12, 21]). The variations of its X-ray spectrum suggest that this cycle is a manifestation of mass-transfer variations, and not a precessing disk [22]. In variance with Cyg X-2, the superorbital modulation of 4U 1820–30 is probably due to the Mazeh & Shaham mechanism [21, 23]. The highly asymmetric X-ray light curve of this cycle, with a complicated profile of the decay branch, also suggests a combination of the Mazeh & Shaham mechanism and an irradiation-driven instability of the donor [24]. Simultaneous monitoring by ASM/*RXTE* and BAT/*Swift* revealed transitions from soft to hard state during some episodes of minimum of soft X-ray luminosity of the superorbital cycle [16].

3. Conclusions

Dense series of X-ray observations from monitors covering time segments of at least several years are necessary to investigate the properties of the long-term activity of LMXBs, hence to study the relevant physical processes involved in these systems. This is necessary for resolving the profiles of the outbursts and the transitions between the high and low states. Only dense mapping will enable us to place these events in the context of the long-term activity of a given system. It will enable us to form a representative ensemble of events (a) in a given X-ray binary system, (b) in a type of X-ray binary systems.

It emerges that important profiles of features of the long-term activity are measurable by the monitors. A very large variety of these features exists. A search for the common properties is therefore needed. Even a search for the accompanying spectral variations is possible with some existing monitors. Changes of the hardness ratios are measurable e.g. by ASM/*RXTE* or by a combination of simultaneous ASM/*RXTE* and BAT/*Swift* observations.

We emphasize the very important role of the spectral region of the X-ray monitor. A very hard X-ray band like the one in BAT/*Swift* sometimes maps quite a different activity (probably coming from a different spectral component) than that detected by monitors observing in soft X-ray band. The time evolution of T_C of outbursts is very little studied mainly because of a lack of data. It has been possible to investigate only very few soft X-ray transients with quite short T_C of less than a year so far.

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References

[1] W. H. G. Lewin, J. van Paradijs, E. P. J. van den Heuvel. *X-Ray Binaries*. Camb. Astrophys. Ser., Vol.26. Cambridge University Press, 1995.

[2] W. H. G. Lewin, M. van der Klis. *Compact stellar X-ray sources*. Cambridge University Press, 2006.

[3] G. Dubus, J.-M. Hameury, J.-P. Lasota. The disc instability model for X-ray transients: Evidence for truncation and irradiation. *A&A* **373**:251–271, 2001. doi:10.1051/0004-6361:20010632.

[4] S. B. Foulkes, C. A. Haswell, J. R. Murray. SPH simulations of irradiation-driven warped accretion discs and the long periods in X-ray binaries. *MNRAS* **401**(2):1275–1289, 2010. doi:10.1111/j.1365-2966.2009.15721.x.

[5] A. M. Levine, H. Bradt, W. Cui, et al. First results from the all-sky monitor on the Rossi X-ray timing explorer. *ApJ* **469**:L33–L36, 1996. doi:10.1086/310260.

[6] S. D. Barthelmy, L. M. Barbier, J. R. Cummings, et al. The Burst Alert Telescope (BAT) on the SWIFT Midex Mission. *Space Sci Rev* **120**:143–164, 2005. doi:10.1007/s11214-005-5096-3.

[7] H. A. Krimm, S. T. Holland, R. H. D. Corbet, et al. The Swift/BAT hard X-ray transient monitor. *ApJS* **209**:14–46, 2013. doi:10.1088/0067-0049/209/1/14.

[8] T. Narita, J. E. Grindlay, D. Barret. ASCA observations of GX 354-0 and KS 1731-260. *ApJ* **547**(1):420–427, 2001. DOI:10.1086/318326.

[9] R. Morrison, D. McCammon. Interstellar photoelectric absorption cross sections, 0.03–10 keV. *ApJ* **270**:119–122, 1983. DOI:10.1086/161102.

[10] N. Vogt. The SU UMa stars – an important sub-group of dwarf novae. *A&A* **88**(1-2):66–76, 1980.

[11] V. Šimon. On the recurrence time and outburst properties of the soft X-ray transient Aquila X-1. *A&A* **381**:151–167, 2002. DOI:10.1051/0004-6361:20011470.

[12] W. C. Priedhorsky, J. Terrell. Long-term observations of X-ray sources – the Aquila–Serpens–Scutum region. *ApJ* **280**:661–670, 1984. DOI:10.1086/162039.

[13] J. Vondrák. A contribution to the problem of smoothing observational data. *BAICz* **20**:349–355, 1969.

[14] J. Vondrák. Problem of smoothing observational data ii. *BAICz* **28**:84–89, 1977.

[15] E. Whittaker, G. Robinson. *The Calculus of Observations*. Blackie & Son Ltd, London, 1946.

[16] J. Tang, W.-F. Yu, Z. Yan. RXTE/ASM and Swift/BAT observations of spectral transitions in bright X-ray binaries in 2005–2010. *RAA* **11**(4):434–444, 2011. DOI:10.1088/1674-4527/11/4/006.

[17] J. Casares, P. A. Charles, E. Kuulkers. The mass of the neutron star in Cygnus X-2 (V1341 Cygni). *ApJ* **493**:L39–L42, 1998. DOI:10.1086/311124.

[18] R. A. D. Wijnands, E. Kuulkers, A. P. Smale. Detection of a ∼78 day period in the RXTE, VELA 5B, and Ariel 5 all-sky monitor data of Cygnus X-2. *ApJ* **473**:L45–L48, 1996. DOI:10.1086/310390.

[19] W. I. Clarkson, P. A. Charles, M. J. Coe, et al. Long-term properties of accretion discs in X-ray binaries – II. Stability of radiation-driven warping. *MNRAS* **343**(4):1213–1223, 2003. DOI:10.1046/j.1365-8711.2003.06761.x.

[20] G. I. Ogilvie, G. Dubus. Precessing warped accretion discs in X-ray binaries. *MNRAS* **320**(4):485–503, 2001. DOI:10.1046/j.1365-8711.2001.04011.x.

[21] Y. Chou, J. Grindlay. Binary and long-term (triple?) modulations of 4U 1820-30 in NGC 6624. *ApJ* **563**(2):934–940, 2001. DOI:10.1086/324038.

[22] P. F. Bloser, J. E. Grindlay, P. Kaaret, et al. RXTE studies of long-term X-ray spectral variations in 4U 1820-30. *ApJ* **542**(2):1000–1015, 2000. DOI:10.1086/317019.

[23] T. Mazeh, J. Shaham. The orbital evolution of close triple systems – The binary eccentricity. *A&A* **77**:145–151, 1979.

[24] V. Šimon. Long-term X-ray activity of the ultra-compact binary 4U 1820-30. *A&A* **405**:199–206, 2003. DOI:10.1051/0004-6361:20030514.