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Investigation of the long-term activity of the binary X-ray sources with the planned satellites

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Abstract. Monitors of X-ray emission are important instruments for observing the long-term activity of cosmic sources on the long timescales (e.g. years). We show the perspectives and possibilities of observing the selected types of X-ray binary sources with the planned satellites *THESEUS* and *eXTP*. The hardness of the X-ray spectrum largely determines the observability of a given object (or a type of objects) with a monitor operating in the specific band. We show the perspectives of detecting and observing outbursts in the soft X-ray transients with the hard X-ray monitors *eXTP*/WFM and *THESEUS*/XGIS. Their broad energy bands and energy resolution will enable to detect the outbursts and the complex spectral changes during these events. We also show the perspectives of observing the binary supersoft X-ray sources with the planned *THESEUS*/SXI. These sources sometimes have the luminosity close to the Eddington limit but their X-ray emission is usually below the band used by the monitors.

Key words: Accretion, accretion disks – X-rays: binaries – stars: neutron – stars: black holes – white dwarfs

1. Introduction

Monitors of X-ray emission are important instruments for observing the long-term activity of cosmic sources on the long timescales (e.g. years and decades). Hardness of the X-ray spectrum determines the observability of a given object (or a type of objects) with a monitor operating in the specific band, so the X-ray emission of some types of objects can remain undetected by some instruments. We show the perspectives and possibilities of observing this activity in the selected types of such sources with the planned satellites *THESEUS* and *eXTP*.

2. Hard X-ray observing with *eXTP*/WFM and *THESEUS*/XGIS

WFM monitor (a set of three coded mask wide field units) onboard *eXTP*, planned to observe in the 2–50 keV band (Zhang et al., 2016), will be suitable for observing the long-term activity of X-ray binaries. Also *THESEUS*/XGIS (2 keV–20 MeV) (Campana et al., 2016) can be used for this purpose because X-ray binaries (the systems in which the neutron star (NS) or the black hole (BH) accretes matter from its close companion (Lewin et al., 1995)) often produce hard X-ray emission (e.g. with energy E of tens of keV), well within the band of WFM and XGIS. The continuum emission (often a composition of the emission components from the inner disk region (thermal radiation) and from the Comptonizing cloud around the accretor – inverse Compton scattering) of these objects by far dominates the X-ray spectrum (e.g. Lewin et al. (1995)).

What can we expect from the data from X-ray monitors? The characteristic features of the long-term activity of a type of X-ray binaries, the outbursts of the soft X-ray transients (SXTs), caused by a thermal-viscous instability of the accretion disk (e.g. Dubus et al. (2001)), can be investigated even in a single-band X-ray light curve (monitors typically observe X-rays with E of a few keV). Even some model predictions regarding to the mass accretion rate (approximated as the soft X-ray flux) are already available in a model of Dubus et al. (2001). These spectral variations are reflected in the differences between the X-ray light curves in various X-ray bands. The light curves from the planned WFM or XGIS observations, divided into several energy sub-bands, will be very important because their broad energy band and their energy resolution will enable to resolve the complex changes during the outbursts.

As an illustration of the features of the long-term activity of the SXTs, we show an outburst of Aql X-1 (Koyama et al., 1981; Chevalier & Ilovaisky, 1991) in Fig. 1. It is a combination of the one-day means of the data from the monitors *ISS*/MAXI (Matsuoka et al., 2009) and *Swift*/BAT (Krimm et al., 2013).

Fig. 1b shows the time evolution of the one-day means of the hardness ratios. These ratios, determined from the MAXI data, are $HR1 = \frac{I_\mathrm{B}}{I_\mathrm{A}}$ and $HR2 = \frac{I_\mathrm{C}}{I_\mathrm{B}}$. The flux I_A is for the 2–4 keV band, I_B for the 4–10 keV band, and I_C for the 10–20 keV band from Fig. 1a. A large difference between the light curve of the outburst in the 15–50 keV band (Fig. 1c) and in the softer bands in Fig. 1a shows the importance of monitoring in the very broad bands like those of *eXTP*/WFM and *THESEUS*/XGIS. Their data can be used for an investigation of the mutually different X-ray light curves in the different E (and the hardness ratios) of such events. This monitoring in a very broad energy band also enables to determine the color vs. color diagrams from the X-ray light curves (Asai et al., 2016).

A division of the observed X-ray emission into several sub-bands can help to assess the role of the emission mechanisms and their evolution with time. Of course, the bands used for Fig. 1 can be modified for the sub-bands into which the WFM or XGIS measurements can be divided. Since most features of the long-term activity occur on the timescales longer than a day, the features in the light curves of outbursts can be well defined even when the data are sampled and binned in time (e.g. when the one-day means are used). This binning enables to increase the signal-to-noise ratio.

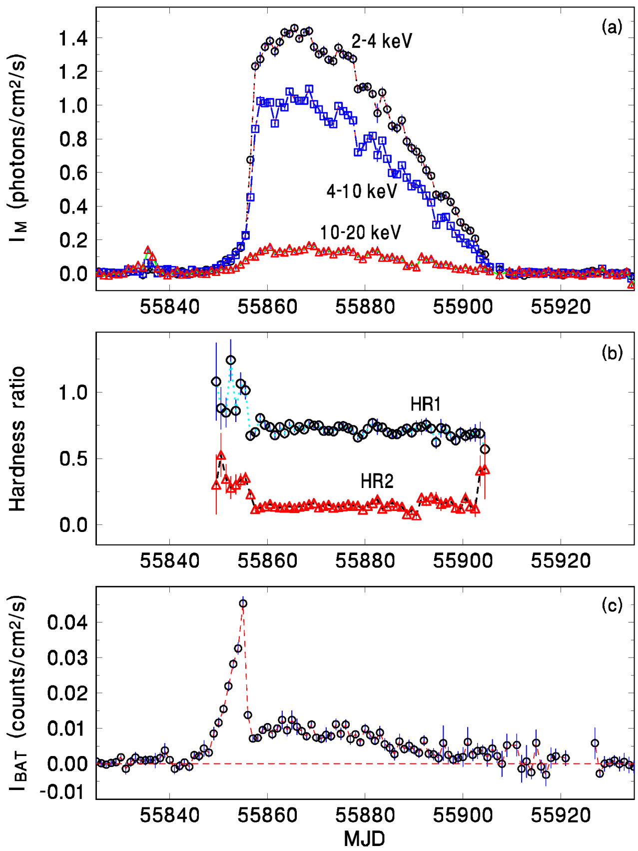

Figure 1. **(a)** Light curve of an example of the outburst of the soft X-ray transient Aql X-1 (MAXI data). Time is expressed as the Modified Julian Date (MJD). Energies of the individual bands are marked. **(b)** The hardness ratios $HR1$ and $HR2$. They are explained in the text. **(c)** Light curve of Aql X-1 in the 15–50 keV band of *Swift*/BAT.

Since both the width and the position of the peak of the outburst largely differ for various energy bands (2–20 keV versus 15–50 keV) (Fig. 1), the large variations of the emitting regions during the outburst are suggested. Ono et al. (2017) present a model consisting of a multi-color disk (MCD) and a Comptonized blackbody, with the flux of the MCD making the dominant peak of the whole outburst. As a result, the light curves in the different X-ray bands differ from each other because of the different dominant emission regions and processes.

The conditions in the disks of the SXTs can be affected by the presence of a very hot inner disk region; it can act as an irradiating source during outburst and is thought to modify the disk structure (e.g. Dubus et al. (2001)). This configuration very strongly influences the X-ray light curve of the outburst. Also the determination of the hardness ratios is important to show the time evolution of the emitting regions. The accompanying variations between the light curves in the different bands of WFM will be important for this research. The duration of the outbursts of the SXTs is from days to months, so even a one-day binning of the WFM data will be sufficient.

The light curve in Fig. 1 shows no clear sign of an exponential decay of the outburst of Aql X-1. This suggests no irradiation of the disk, when the model of Dubus et al. (2001) is applied. This is an important feature because the decaying branches observed in the 1.5–12 keV band by the *RXTE*/ASM monitor (Levine et al., 1996) differed for the individual outbursts in a similar object, 4U 1608–52 (Šimon, 2004).

Investigations of the recurrence time of the outbursts of the SXTs, $T_{\rm C}$, require the X-ray monitors. The reason is that while the typical durations of the outbursts of the SXTs are from weeks to months, $T_{\rm C}$ are from months to decades (e.g. Lewin et al. (1995)). It is therefore reasonable to expect that *eXTP*/WFM and *THESEUS*/XGIS will observe a series of outbursts of some SXTs with frequent outbursts ($T_{\rm C}$ of less than 1 year) like e.g. Aql X-1 (e.g. Šimon (2002)) or 4U 1608-52 (e.g. Šimon (2004)). Because a given monitor is able to operate for several years, even a basic knowledge of the time evolution of $T_{\rm C}$ of most SXTs requires the data from several monitors.

The individual outbursts of a given SXT can have very different energy outputs (fluences) (fluence is the flux integrated over the duration of the whole outburst in a given band). This parameter, measurable by the monitors, sometimes largely differs even for the neighboring outbursts but this difference of the energy output does not influence the length of $T_{\rm C}$ of a given SXT. In the interpretation, only a small fraction of mass of the accretion disk is accreted during a single outburst in such a case. The analyses of Šimon (2002) and Šimon (2017) show that the length of $T_{\rm C}$ displays episodes both of a decrease and an increase of the length. The available data show that the length of $T_{\rm C}$ varies much more gradually than the fluence or the peak intensity of the outbursts.

Another important role of the X-ray monitors sensitive in a broad band are the observations of the cycles like the one superimposed on a very long (about 600 d) outburst of the LMXB SXT XTE J1701–462. Its length displayed a large and gradual increase from $\sim$16 to $\sim$26 days. Since this cycle was detected only by *RXTE*/ASM (1.5–12 keV), but not by *Swift*/BAT (15–50 keV), it was interpreted as coming only from the component emitting the soft X-rays (a superorbital cycle caused by tilting and warping of the irradiated disk) (Šimon, 2015). The complexity of the detected features of the time variations was caused by the fact that this source emitted X-rays from several regions (Homan et al., 2007; Lin et al., 2009).

3. Supersoft X-ray sources with *THESEUS*/SXI

The binary supersoft X-ray sources are the very unique emitters because their matter is accreted onto the white dwarf (WD) from a close companion at an extremely high rate. This leads to steady-state thermonuclear burning of accreted hydrogen on the surface of the WD (van den Heuvel et al., 1992). It largely contributes to their luminosity.

An X-ray emission of the very hot atmosphere of the WD (with the spectrum similar to black body and the luminosity even at the Eddington limit) in the band with $E < 1.5$ keV is produced (Popham & di Stefano, 1996). In the absence of absorption which steeply increases with the decreasing E (Morrison & McCammon, 1983), the peak luminosity occurs at $E \approx 0.3$ keV. The intensity then steeply decreases with growing E, being by more than about three orders of magnitude smaller at $E \approx 1.5$ keV.

The observed anti-correlation of the optical and soft X-ray intensities in the long-term activity of some of these objects is interpreted in terms of the very large sensitivity of the supersoft X-ray emission to two effects: absorption intrinsic to the source (Greiner & van Teeseling, 1998), and changes of the radius of the hydrogen burning envelope on the WD (Reinsch et al., 2000). A division of the observed X-ray emission into several energy bands can help to assess the role of the above-mentioned mechanisms and their evolution with time. However, this very soft X-ray emission is beyond the band of sensitivity of most X-ray monitors, so the investigations of the long-term activity of these objects are usually conducted in the optical band.

V Sge with the orbital period $P_{\rm orb} = 0.514195$ d (Herbig et al., 1965) can serve as an example of the complex long-term activity of the transient supersoft X-ray sources (Hachisu & Kato, 2003). The optical luminosity, generated mainly by the accretion disk, is roughly anti-correlated with the X-ray luminosity (mainly from the hydrogen burning) (Greiner & van Teeseling, 1998). The positions of their X-ray measurements are included in Fig. 2a. When the X-ray spectrum of V Sge in the 0.1–2.4 keV band is "very soft", the X-ray luminosity is significantly higher than when it is "hard".

Transitions between the states of activity of V Sge are usually considerably faster than the duration of the state, so an observing within a given state is expected by *THESEUS*/SXI (O'Brien et al., 2018) (Fig. 2a). The WWZ-transform (method of Foster (1996)) shows an evolution of activity with time (Fig. 2b). The value of WWZ indicates whether or not there is a periodic fluctuation at a given time at a given frequency. Although the transitions between the high and low states are cyclic (Fig. 2b), this cycle displays a complicated evolution and is only intermittently present. These transitions sometimes even temporarily disappear (Šimon & Mattei, 1999).

Also RX J0513–69 displays the long-term activity similar to that of V Sge. It is detectable as a very soft X-ray source only during its recurrent optical low-state episodes (Reinsch et al., 2000). The anti-correlation of the very soft

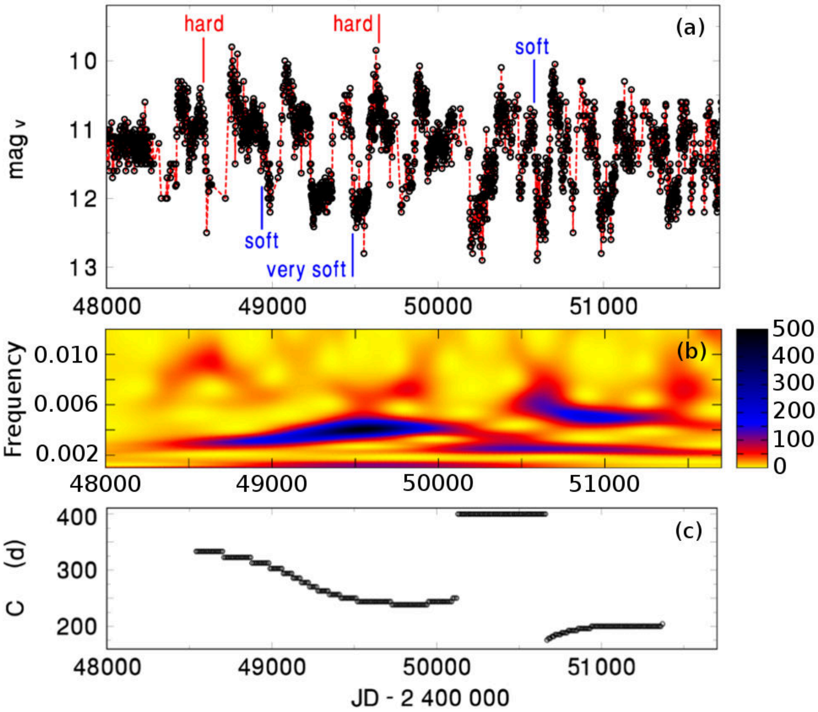

Figure 2. **(a)** The optical long-term activity of the supersoft X-ray source V Sge (one-day means of the AAVSO and AFOEV data (Kafka, 2016)). The times and characteristics of the X-ray spectra in the *ROSAT* observations are from Greiner & van Teeseling (1998). **(b)** Cycles in the high-low state transitions (method of the WWZ–transform of Foster (1996)). Frequency is given in d^{-1}. The color scale represents the values of WWZ (see the scale). The higher the WWZ value, the better defined the cycle-length. **(c)** The best cycle-length C measured in days. Only the segments with the amplitude larger than 38 percent of its peak value were included. Updated from Šimon (2016).

X-ray and the optical fluxes argues for a multifrequency monitoring e.g. with the instruments SXI (O'Brien et al., 2018) and IRT (Götz et al., 2018) onboard *THESEUS*. Monitoring of various binary supersoft X-ray sources can shed more light on the activity of such objects and its more structured classification.

We also emphasize that it is important to answer the question in which states of activity such objects are detectable in the X-ray band and how this activity evolves on the long timescales (months, years). The monitor which is planned to observe in the band with $E < 1.5$ keV can help us to detect the long-term activity of these sources in the X-ray band.

4. Conclusions

The detectability of an object strongly depends on the energy band of the X-ray monitor. We also emphasize that the soft X-ray activity of a given source can be different from that in the hard X-ray band.

The hard X-ray monitors (*THESEUS*/XGIS, *eXTP*/WFM) are suitable for observing the NS and the BH accretors. The soft X-ray monitor *THESEUS*/SXI can be used also for observing the binary supersoft X-ray sources.

The outbursts of the SXTs are usually unpredictable. Their average T_C and its complicated variations can be determined only from a long (years to decades) series of observations. Since the time of operation of a given monitor is often several years, also a follow-up observing with the future monitors is very needed.

The light curves of the SXT outbursts in a given X-ray band differ for the individual events even in the same object. The large structural changes of the emitting regions occur during the outburst (e.g. the time of the peak flux of the far X-ray emission (15–50 keV) can occur when the soft X-ray flux (e.g. 2–4 keV) is still rising to its peak).

The near-IR monitor *THESEUS*/IRT is suitable for observing all types of binary X-ray sources, but it appears to be very important also for detecting and/or observing of the optical counterparts of X-ray transients and the correlations of the optical and X-ray states in the binary supersoft X-ray sources.

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