Contrib. Astron. Obs. Skalnaté Pleso **47**, 184 – 191, (2017)

Perspectives of the lobster-eye telescope: The promising types of cosmic X-ray sources

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Received: April 12, 2017; Accepted: June 12, 2017

Abstract. We show the astrophysical aspects of observing the X-ray sky with the planned lobster-eye telescope. This instrument is important because it is able to provide wide-field X-ray imaging. For the testing observations, we propose to include also X-ray binaries in which matter transfers onto the compact object (mostly the neutron star). We show the typical features of the long-term X-ray activity of such objects. Observing in the soft X-ray band is the most promising because their X-ray intensity is the highest in this band. Since these X-ray sources tend to concentrate toward the center of our Galaxy, several of them can be present in the field of view of the tested instrument.

Key words: X-rays: binaries – Radiation mechanisms: general – Methods: observational

1. The importance of X-ray monitoring

Monitoring enables to identify the type of the object and to place the events (e.g. outbursts) in the context of its long-term activity. This approach also enables to form a representative ensemble of events (e.g. outbursts, different states of activity) in (a) a given object (system), (b) in a type of objects (systems). This is important for our understanding of the physical processes involved. The outbursts of the cosmic X-ray sources are often unpredictable, and many sources are discovered only by the outburst. Wide-field X-ray monitoring is therefore necessary.

1.1. Previous or current X-ray monitors

We summarize the parameters of several X-ray monitors.

ASM/*RXTE* was a monitor for observing in the medium/hard X-ray band. It operated onboard Rossi X-Ray Timing Explorer (*RXTE*) in the years 1996–2012 (Levine et al., 1996). ASM consisted of three shadow cameras with a 6×90 degrees of field of view. It operated in the energy range of 1.5–12 keV, which could be divided into the bands of 1.5–3 keV, 3–5 keV, and 5–12 keV. The integration time was 90 s, and 80 percent of the sky could be mapped every

90 min. One-day means were usually used to increase the sensitivity. The spatial resolution was 3×15 arcmin, with the sensitivity of about 13 mCrab for the one-day means.

MAXI/*ISS* is the current monitor for medium/hard X-rays. It has been operating onboard ISS since 2010. It uses slit cameras in six units (160×1.5 degrees of field of view). Its energy range of 2–20 keV is divided into three bands: 2–4 keV, 4–10 keV, 10–20 keV. The source is observed twice per 92 min orbit. The one-day means of data are usually used to increase the sensitivity (Matsuoka et al., 2009).

BAT/*Swift* is the current monitor for the very hard X-rays onboard NASA *Swift* (since 2004) (Krimm et al., 2013). It uses the coded mask. The field of view is 1.4 sr (partially-coded). The energy range is 15–150 keV (usually 15–50 keV for monitoring of X-ray sources).

Monitoring of the Galactic plane is part of the Core Programme of the ESA satellite *INTEGRAL*. The scans occur every 12 days. They are obtained by a "slew - and stare" maneuver of *INTEGRAL* along the accessible part of the Galactic plane. The X-ray and γ-ray observations are conducted by IBIS, SPI, and JEM-X, accompanied by the V-band OMC. The exposure of a given field is 2200 s (Winkler et al., 2003).

2. Properties of the tested lobster-eye telescope

The prepared lobster-eye telescope represents a novel type of optics for X-rays (e.g. (Hudec et al., 2004; Sveda et al., 2004; Hudec et al., 2007, 2015). The field of view will be approximately 3×3 degrees. It will use the detector Timepix. It is a compact pixel detector (256×256 square pixels, $55 \times 55\,\mu$m each). It is suitable for detecting extraterrestrial X-rays due to its low noise characteristics, which enables measuring without special cooling. It operates in the energy range of 5–20 keV (Baca et al., 2016). The gain of the lobster-eye optics is the biggest in the soft X-ray band (the energy $E \approx 5$ keV) and gradually decreases, being by about four times smaller at $E = 20$ keV (Baca et al., 2016).

This testing flight of *VZLUSAT-1* aims to verify the functionality of the lobster-eye optics and the detector in space. It is rather a technological mission. Nevertheless, it can also observe celestial sources. The uncertainty of the stabilization is ± 10 degrees. The instrument is expected to be able to detect a source even if its signal on the detector is only 1 or 2 photons.

3. The calibrating X-ray source

The Crab nebula can be used as a calibrating source in the X-ray band. In the 1.5–12 keV band used by the ASM/*RXTE* monitor, the flux of 1 Crab corresponds to the flux $F = 2.67 \times 10^{-8}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. The moving averages show that the flux was almost stable within the observing uncertainties during the time interval of about 13 years of observing by this monitor (Šimon, 2015b). For ASM/*RXTE*, the flux of the Crab nebula in the 1.5–12 keV band is: 1 Crab = 76 ct s^{-1}.

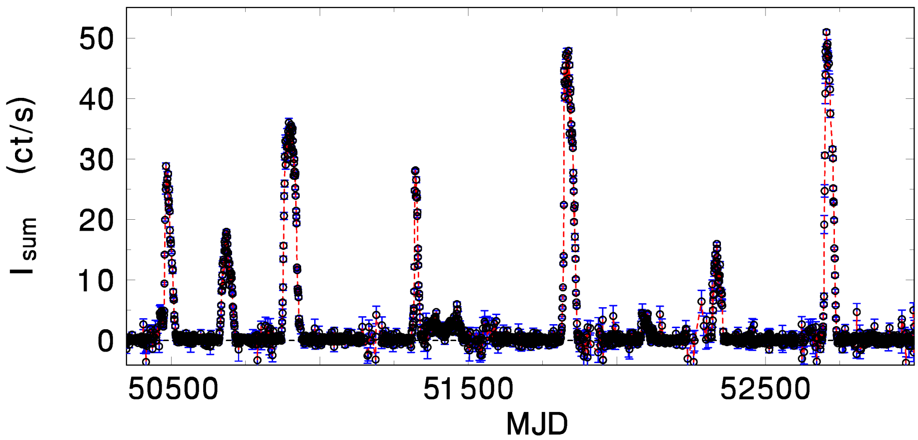

Figure 1. Example of activity of the soft X-ray transient (LMXB) Aql X-1 in the 1.5–12 keV band. The ASM/*RXTE* data (one-day means) with the band similar to the one of the proposed lobster-eye telescope were used. The uncertainties of the flux are marked but they are often comparable to the size of the symbol. To guide the eye, the data were connected by the line.

4. Promising cosmic sources for the test

We show the astrophysical aspects of observing the X-ray sky during the testing flight of *VZLUSAT-1*. The detection of X-ray emission of the Sun will be the most important for this flight but also cosmic X-ray binary sources are often strong X-ray emitters, which makes them the promising sources for the test. These systems contain the neutron star or the black hole, accreting matter from the companion. X-rays come from the close vicinity of the compact object. The reviews can be found in Lewin et al. (1995) and Lewin & van der Klis (2006). The continuum produced by several components (e.g. the inverse Compton emission, the multicolor disk) dominates in the X-ray emission of X-ray binaries (e.g. (Lewin et al., 1995; Lewin & van der Klis, 2006)). These objects are the most luminous in the soft X-rays (E of about 2 keV).

In low-mass X-ray binaries (LMXBs), the mass transfer usually occurs via Roche lobe overflow because the mass-donating star (donor) of a late spectral type fills its lobe. The transferring mass forms an accretion disk which embeds the compact object (the neutron star, the black hole). The inner disk region is the source of thermal radiation (soft X-rays with the energies E up to several keV). In the close vicinity of the compact object, a Comptonizing cloud (inverse Compton scattering) can produce hard X-rays (with E up to more than 10 keV).

The accretion disk suffers from a thermal-viscous instability if the time-averaged mass transfer rate $\dot{m}_{\rm av}$ from the donor to the compact accretor lies between certain limits. This causes occasional outbursts in LMXBs. Such systems are called soft X-ray transients (SXTs) (e.g. Dubus et al. (2001)). The outbursts of SXTs are usually unpredictable; their mean recurrence time (cycle-length) and its time variations can be determined only from a long (e.g. years) series of observations. Since the duration of outbursts of LMXBs (SXTs) is on the order of several weeks to several months, it is reasonable to expect good coverage of the profile of such an event in the data from the monitors. An example of this long-term activity is displayed in Fig. 1. The X-ray flux of the SXT Aql X-1 is highly variable. This source is detectable by the monitors only during the outbursts. Aql X-1 is brighter than 0.5 Crabs in some outbursts. Most outbursts in Fig. 1 were brighter than 0.25 Crabs.

On the other hand, LMXBs called (quasi)persistent X-ray sources are often in the high state (luminous in X-rays) but they display variations of the X-ray flux even by a factor of several on the typical timescales of weeks and months. An example, Sco X-1, is displayed in Fig. 2. Sco X-1 is the brightest X-ray binary in the soft X-ray band. Since it is a persistent X-ray source, it is the most suitable object for the initial testing. Its intense X-ray emission is detectable every time. Figure 2 shows that the flux of the system is variable, but Sco X-1 is always very bright in soft X-rays (1.5–12 keV). Its flux is about 11 Crabs because 1 Crab = 76 ct s^{-1} in the ASM/*RXTE* data.

An increasing $\dot{m}_{\rm av}$ from the donor to the disk leads to the more frequent outbursts. After a further increase of $\dot{m}_{\rm av}$ above some limit, the accretion disk becomes ionized out to its outer rim and thermally stable. The X-ray flux of the system therefore stabilizes. A sequence according to van Paradijs (1996) shows a gradual change of the long-term activity from the large-amplitude, isolated outbursts starting from the baseline quiescent state to the dominant relatively small fluctuations in the high state. Moreover, the occasional transitions of some of such systems between the high and low states of luminosity are usually fast (e.g. days) and unpredictable. Monitors are therefore needed for investigating the long-term activity.

In the high state or outburst, the X-ray flux of a typical X-ray spectrum peaks in the soft X-ray band (roughly in the vicinity of E of approx. 2 keV) (e.g. (Laros & Singer, 1976; Lin et al., 2009)). The intensity then gradually decreases with the growing E, so it is better to construct the monitors which are able to observe in the soft X-ray band to detect the faint sources. The origin of X-ray emission is complex, which can cause that the X-ray emission detected in the different X-ray bands can come from the different emitting regions of the binary. The features in the light curves of a given source can thus differ.

For example, our previous analysis of the data from the monitors ASM/*RXTE* (1.5–12 keV) and BAT/*Swift* (15–50 keV) (Šimon, 2015a) of the neutron-star LMXB SXT XTE J1701–462 showed this fact. The complexity of the detected features was caused by the fact that this source emitted X-rays from the different regions during its very long (about 600 d) outburst (Homan et al., 2007; Lin et al., 2009). The X-ray spectrum is continuous and its complexity is caused by the fact that it comes from several emitting regions. Using the results of spectroscopy of Lin et al. (2009), the 1.5–12 keV data represent mainly the luminosity of multicolor disk while the luminosity of the blackbody component contribute mainly to the intensity in the harder X-ray band. This source was relatively bright during the outburst in the X-ray band of ASM/*RXTE*, about 0.75 Crabs in the peak of the outburst, and about 0.25 Crabs during a long plateau, so such events can be detected also by the proposed lobster-eye telescope. Its supposed detector Timepix will be sensitive in the band of 5–20 keV, which can partly connect the bands of ASM and BAT.

High-mass X-ray binaries (HMXBs) contain the compact object which is usually the neutron star or the black hole. The mass-donating component is a high-mass star of an early spectral type (O, B). Various accretion modes can be present in HMXBs: (a) Roche lobe overflow (if the mass-donating star fills its lobe), (b) wind accretion if the mass-donating star underfills its lobe, (c) periastron passage in the case of a binary with a highly eccentric orbit. HMXBs with Roche lobe overflow can display the long-term X-ray activity similar to those of LMXBs. In HMXBs with the eccentric orbit, the periastron passages are often accompanied by an episodic large brightening in the X-ray band.

In summary, the following types of sources are promising for the detection by the testing type of the proposed monitor: (a) low-mass X-ray binaries (LMXBs), (b) high-mass X-ray binaries (HMXBs). Both of these types can be X-ray transients or persistent X-ray sources.

5. Analysis of data of faint X-ray sources

The proper approaches are needed for an analysis of the data of faint X-ray sources from the testing lobster-eye monitor.

Binning of X-ray data enables to analyze faint sources, although it smooths the profiles of the features. Determining the mean levels of X-ray flux in some states of activity is possible e.g. for the high states of the sources.

Also a smoothing of the X-ray data through the orbital modulation of the source is possible because the large features of the long-term activity (e.g. outbursts, individual episodes of the high states) occur on the significantly longer timescales. While the orbital period of most LMXBs is shorter than a day (Ritter & Kolb, 2003), the typical duration of an outburst is several weeks. In persistent X-ray sources, the fluctuations of the flux are often gradual and on the timescales of weeks.

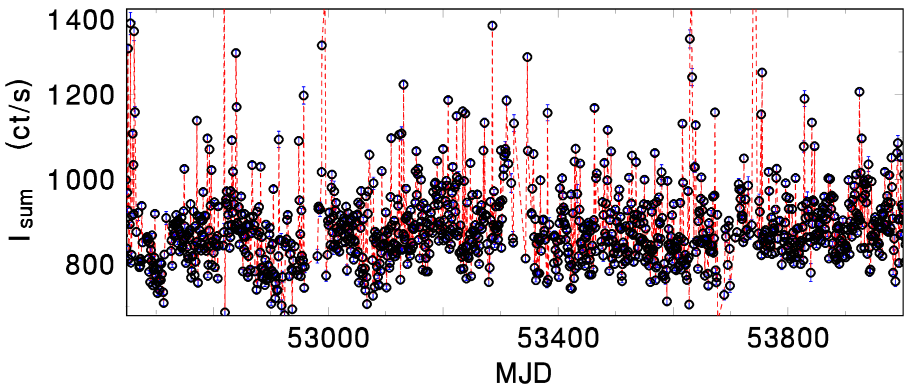

Figure 2. Example of activity of the very bright persistent source (LMXB) Sco X-1 in the 1.5–12 keV band. The ASM/*RXTE* data (one-day means) with the band similar to the one of the proposed lobster-eye telescope were used. The uncertainties of the flux are marked but they are often comparable to the size of the symbol. To guide the eye, the data were connected by the line. (Modified from Šimon (2014).)

6. Distribution of X-ray binaries in the sky

Taking the distribution of X-ray binaries in the Galaxy into account is important for making the strategy of monitoring with the testing lobster-eye telescope. The catalog by Liu et al. (2007) shows that both transient and persistent LMXBs concentrate toward the Galactic plane and the Galactic bulge. HMXBs strongly concentrate toward the Galactic plane but not toward the bulge (Liu et al., 2006). This distribution is displayed in Fig. 3.

The above-mentioned regions are therefore very suitable areas for monitoring with the lobster-eye telescope. It is therefore not necessary to monitor the whole sky for the testing. The field of view of the proposed instrument will be approximately 3×4 degrees. Several such objects can thus be found in the field of view.

7. Conclusions

We argue that the X-ray binaries in which matter accretes onto the neutron star or the black hole are the promising cosmic objects even for the tests of the prepared lobster-eye telescope onboard *VZLUSAT-1*. These objects are the most luminous in the soft X-rays, with the X-ray flux only gradually decreasing from the peak at E of about 1–3 keV toward the higher energies. Small changes of the band of sensitivity (e.g. by E of several keV) are therefore not very important for the performance of this monitor and the detection of the sources.

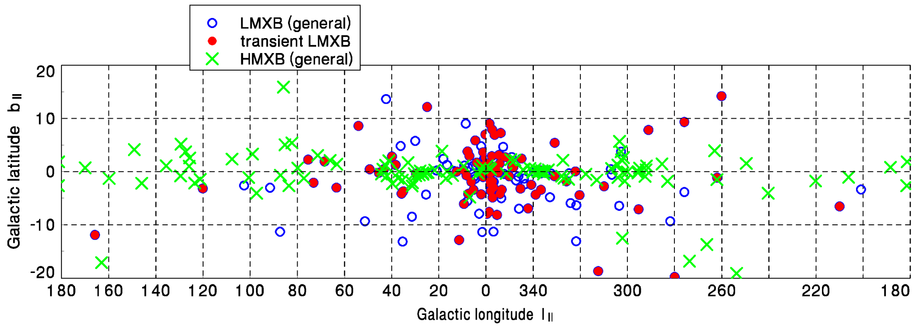

Figure 3. Distribution of LMXBs and HMXBs in the sky. The direction toward the center of the Galaxy is in the center of the plot. The data from the catalogs of Liu et al. (2007) and Liu et al. (2006) were used.

Also the accompanying X-ray spectral variations (changes of the hardness ratios) (e.g. when various states of activity are compared) are measurable by the lobster-eye monitor with the detector Timepix. We emphasize the important role of the spectral region of the X-ray monitor. The proposed detector Timepix with the band of sensitivity in 5–20 keV is very suitable for observing these sources.

It is also necessary to keep in mind that the character of activity can vary with the changes of the X-ray band. For example, the very hard X-ray band like the one in BAT/*Swift* sometimes even maps a different activity of a given source than the monitor observing in soft X-rays (e.g. E of several keV).

As regards the identification of objects in the testing lobster-eye data, it is also possible to compare their position and state of activity with the simultaneous observations of other currently observing X-ray monitors (e.g. BAT/*Swift*, MAXI/*ISS*). In this regard, a simultaneous monitoring of the same object with several monitors will give a possibility to determine the hardness ratio of the X-ray emission.

Although the uncertainty of the stabilization of this satellite is ± 10 degrees, the instrument is expected to be able to detect a source even if its signal on the detector is only 1 or 2 photons. It is therefore reasonable to expect the detection of the celestial sources which cluster toward the center of the Galaxy.

Acknowledgements. This study was supported by grant 13-33324S, provided by the Grant Agency of the Czech Republic. This research has made use of the observations provided by the ASM/RXTE team and public data from Swift/BAT transient monitor provided by the Swift/BAT team. I thank Dr. Vladimír Dániel for a discussion. I also thank Prof. Petr Harmanec for providing me with the code HEC13. The Fortran source version, compiled version and brief instructions on how to use the program can

be obtained at
http://astro.troja.mff.cuni.cz/ftp/hec/HEC13/

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