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Lobster-eye X-ray monitors: astrophysical aspects

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Abstract. We present and discuss the recent progress in design of wide field X-ray monitors with Lobster-eye X-ray optics, with emphasis on astrophysical aspects and justification.

Key words. High-energy sources – Satellites: X-rays – Optics: X-rays

1. Introduction

Achievements of the last decades of X-ray astronomy are related to imaging X-ray telescopes. The use of X-ray optics allows imaging, precise localization, photometry, spectroscopy, variability studies, and estimation of the physical parameters of X-ray emitting regions. The space experiments with X-ray optics are also well suited for monitoring of X-ray sky for variable and transient objects including X-ray novae, X-ray transients, X-ray flares on stars and Active Galactic Nuclei (AGNs), galactic bulge sources, X-ray binaries, SGRs (Soft Gamma Ray Repeaters) and X-ray afterglows of GRBs (Gamma Ray Bursts). However, most of the past and recent X-ray space experiments were based on use of Wolter type X-ray optics with a rather limited field of view (FOV), typically less than 1 degree diameter. Such experiments are not suitable for providing dense sky X-ray monitoring. Instrumentation able to fulfil the goal of sensitive all-sky X-ray monitoring must be based on wide-field optics. The Lobster-eye X-ray lenses offer effective solution for these goals.

Below we give a list of the past and existing X-ray monitors onboard various satellites:

- Vela-5B (1969–1979) 3–12 keV
- Uhuru (SAS-1) (1970–1973) 2–20 keV
- Ariel 5 (1974–1980) 3–6 keV
- Tenma (Astro B) (1983–1985) 2–10 keV
- Ginga (Astro-C) (1987–1991) 1–20 keV
- Granat (1989–1998) 6–120 keV
- ROSAT (1990–1999) 0.1–2.5 keV (All sky-survey, but long-term monitoring of only several objects)
- CGRO (1991–2000) 20–1000 keV
- INTEGRAL (2002 – present) 15 keV–8 MeV
- AGILE (2007 – present) 10–40 keV
- ASM/RXTE (1996 – present) 1.5–12 keV (sensitivity 30 mCrab)

It can be seen from this list that most X-ray all-sky monitors only operated for a short time interval and often only in a relatively

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hard band. The hard band and low sensitivity of these monitors enabled them to detect only the brightest sources. Most of these detected sources contained only the neutron star (NS) or the black hole (BH). For instance, investigation of the long-term activity of the wide category of cataclysmic variables was thus very limited (the still operating ASM/RXTE can reliably detect only three cataclysmic variables and usually only in the states of their bright X-ray emission). We thus argue in favor of developing and using more sensitive X-ray monitors.

2. Lobster eye wide field X-ray optics

The principle of Lobster-eye (LE) type wide-field X-ray optics was published by Angel (1979). The full lobster-eye optical grazing incidence X-ray objective consists of numerous tiny square cells located on the sphere and is similar to the reflective eyes of macruran crustaceans such as lobsters or crayfish. An alternative arrangement based on two sets of planparallel plates was proposed by Schmidt (1975).

The wide-field mirror modules offer advantageous application in astrophysics. The future of X-ray astronomy and astrophysics requires not only detailed observations of particular triggers, but also precise and highly sensitive X-ray sky surveys, patrol and monitoring. The X-ray counterparts of GRBs may serve as an excellent example. The X-ray identification of GRBs has lead to great improvements in study and understanding of these sources and especially has allowed identifications at other wavelengths due to a better localization accuracy provided in X-rays if compared with gamma-ray observations. Since most of GRBs seem to be accompanied by X-ray emission, the future systematic monitoring of these X-ray transients/afterglows is extremely important.

Results of analyzes and simulations of lobster-eye X-ray telescopes have indicated that they would be able to monitor the X-ray sky at an unprecedented level of sensitivity, an order of magnitude better than any previous X-ray all-sky monitor. Limits as faint as 10^{-12} erg cm^{-2} s^{-1} for daily observation in soft X-ray range are expected to be achieved, allowing monitoring of all classes of X-ray sources, not only X-ray binaries, but also fainter classes such as AGNs, coronal sources, cataclysmic variables, as well as fast X-ray transients including gamma-ray bursts and the nearby Type II supernovae. For pointed observations, limits better than 10^{-14} erg cm^{-2} s^{-1} (0.5 to 3 keV) could be obtained, sufficient enough to detect X-ray afterglows of GRBs. These values were estimated for Lobster-eye X-ray monitors with Lobster-eye optics in Schmidt MFO (Multi-Foil Optics) configuration (e.g. Hudec et al. 2004). We note that this type of wide-field X-ray optics exhibits large effective area which results in high sensitivity when compared with alternative solutions. Results of X-ray tests of MFO LE modules were published e.g. by Tichý et al. (2011).

Fig. 1. The LE module (MFO Schmidt arrangement) with the focal length of 250 mm suitable for application on a nanosatellite (top) and the LE module based on gold-coated glass foils 100 micron thick in detail (below).

The LE modules may be small and light, enabling to consider applications in small satellites, and even nanosatellites (Tichý et al. 2009a,b) (Fig. 1). The LE based on MFO technology can offer high gains of order of 100 to 1000, energy coverage up to 10 keV, and angular resolutions of the order of a few arcmin (e.g. Hudec et al. 2004, 2008).

3. Scientific justification

Generation of X-ray emission is a natural product of accretion of matter onto the compact objects (white dwarfs (WDs), NSs, BHs) in the binary systems (cataclysmic variables, X-ray binaries of various types). Accretion process and/or the processes on the surface of the compact object are the dominant sources of X-ray luminosity. X-ray emission of these systems undergoes significant variations on various timescales, from the very fast ones (fraction of second), through the medium fast (days), to the long timescales (years, decades), not speaking about the evolutionary processes.

The long-term variations of the X-ray emission are poorly understood mainly because of the lack of a sufficiently long data coverage. This is caused by the fact that the observing strategies of most existing and previous satellites only concentrated on the pointing to a sample of objects, with a limited observing time allocated for a given object (typically at most several days). Although this strategy enables to study faint sources with high temporal and/or spectral resolution, the information of the long-term processes is lacking. Our understanding of the physical processes in a given object or a category of objects cannot be considered to be plausible if the investigation of the physical processes governing the long-term activity is not carried out.

3.1. Candidate objects for X-ray monitoring with LE monitors

Here we list the types of promising objects located in our Galaxy and in the Magellanic Clouds. Reviews of these systems can be found in e.g. Warner (1995) and Lewin & van der Klis (2006).

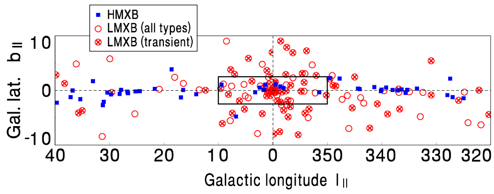

Fig. 2. The field of the center of the Galaxy (20 × 80 deg). The positions of known LMXBs and HMXBs are marked. They come from the catalogues of LMXBs (Liu et al. 2007) and HMXBs (Liu et al. 2006). Most of these systems concentrate toward the Galactic plane and the Galactic bulge. The field proposed for the monitoring by lobster is marked by the oblong. It contains a number of known LMXBs and HMXBs.

Cataclysmic variables (CVs) of various subtypes:

- Dwarf novae
- Nova-like CVs
- Polars
- Intermediate polars (IPs)
- (Classical) novae
- Recurrent novae
- Super-soft X-ray sources
- Symbiotic systems

X-ray binaries of various subtypes:

- High-mass X-ray binaries (HMXBs)
- Low-mass X-ray binaries (LMXBs)
- X-ray transients (XTs) – subtype of HMXBs and LMXBs (XTs can be sorted as follows: (a) soft X-ray transients (SXTs), (b) hard X-ray transients, (c) very fast X-ray transients)
- Persistent X-ray sources – subtype of HMXBs and LMXBs
- Microquasars – subtype of HMXBs and LMXBs

3.2. The detection rates

We briefly discuss an approximate number of objects which can be monitored by LE X-ray monitor. The number of known CVs located in our Galaxy is more than 1000 and still grows. The number of known X-ray binaries (both LMXBs and HMXBs) located in our Galaxy is several hundred and still grows. It is therefore clear that there are more than 1000 known systems in our Galaxy that can be monitored with our lobster-eye telescope. Additional objects are located in two nearby galaxies – the Magellanic Clouds.

We argue that monitoring of a large part of the sky is needed, not only monitoring of (hence pointing to) the already known objects. The reason is that most transients (e.g. objects with outbursts) were discovered only in outburst, not in quiescence before this event. A lot of 'sleeping' transients of various types thus exist.

The field of the center of the Galaxy looks very promising for monitoring with LE onboad a nanosatellite. The reason is obvious. Most of LMXBs and HMXBs concentrate toward the Galactic plane and the Galactic bulge (Fig. 2). FOV of the proposed LE monitor is about 5×5 deg. The oblong in Fig. 2 represents the area suitable for monitoring. It consists of four FOVs. This proposed field contains many known sources. Typical light curve of a persistent source (i.e. source bright in the X-ray band all the time), GX 3+1, is displayed in Fig. 3. Seasonal gaps are short. In addition, it is reasonable to expect that new transient sources will appear during the monitoring.

The amplitude of outburst can be more than an order of magnitude (in transients even more than 100). This suggests that we can obtain meaningful information even by a study of faint objects whose low X-ray intensities are affected by a noticeable uncertainty.

3.3. Perspectives

We briefly discuss the perspectives of analysis of the X-ray data obtained with the proposed lobster-eye monitor.

Transitions between the activity states (e.g. outbursts (especially the rises and decays), high/low states) are often unpredictable. Monitors with wide field of view are thus needed to resolve them. Occasional pointing is not enough due to the following reasons. Many pieces of information on the time evolution are lost without long and relatively dense (e.g. once a day or several times a week) time coverage. Also time allocation of observing with a satellite has to be justified (search for unexpected behavior of the object is usually not approved).

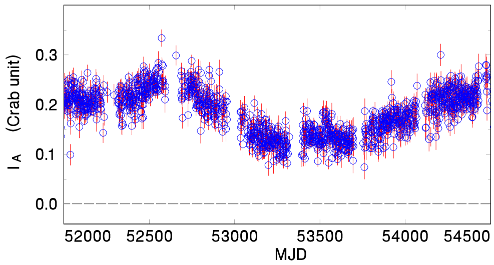

Fig. 3. The light curve of a persistent source in the 1.5–3 keV band. This band is chosen because it is similar to the band of the peak sensitivity of the proposed lobster-eye telescope. The activity of GX 3+1 observed by ASM/RXTE is taken as an example. Intensities are re-calculated into Crabs.

The systems that undergo outbursts (e.g. SXTs and dwarf novae) are particularly promising targets for our monitoring. Features in the outburst X-ray light curves can be observed by our telescope since the outburst often lasts for several days, sometimes even for several months. Even observations with several days long gaps are thus very valuable for our study of the properties of many outbursts.

A very large variety of profiles exists in SXTs and dwarf novae (the individual outbursts even in a single system display different profiles). Search for the common features is thus needed. A lot of results can be achieved even by investigating the profiles of the X-ray light curves obtained in a single band, without using hardness ratios. The parameters of irradiation of the accretion disk (e.g. dimensions and luminosity of the irradiating body, profile of the disk), evolution of the irradiating body during outburst, evolution of spiral arms in the disk are predicted to influence the profile of the light curve of the outburst, hence they can be studied by our monitor.

Mapping of the rising branch of outburst also gives us a hope to determine where the outburst is triggerred (in which region of the accretion disk) and which role the advectiondominated accretion flow (ADAF) plays in SXTs.

We emphasize that to determine a meaningful ensemble of outbursts, monitoring is necessary to obtain a sufficient number of well-mapped outbursts in a given object (e.g. SXT and dwarf nova). The advanced stadium of analysis will be placing these events and findings in the context of the long-term activity of a given system and of a category of systems.

Also search for the relation between the outburst properties and the long-term activity of SXT and dwarf nova is very important. We also stress the importance of evolution of the recurrence time (cycle-length) of outbursts in SXTs and dwarf novae. It is important to investigate the relation of the recurrence time and the properties of outbursts not only in a given object, but also in the category of objects.

Some X-ray binaries (e.g. Her X-1) were observed to display cyclic variations of their X-ray intensity on the timescale of several tens to more than a hundred days (e.g. Clarkson et al. 2003). The amplitude of such variations ranges from less than 10 percent to several tens of percent. Since these superorbital intensity variations are often unstable on longer timescales, the monitoring is necessary to determine the characteristics of the behavior of the system.

4. Conclusion

The Lobster-eye X-ray optical systems offer alternative solution for many future goals both in space and in laboratory. The items discussed in this paper emphasize the very important role of X-ray monitors in our understanding of the processes operating in X-ray sources. The results obtained in the field of very wide field X-ray telescopes of Lobster-eye type are very promising. The prototypes developed and tested confirm that these telescopes are fully feasible and can achieve fine angular resolutions of 4 arcmin or better over a wide field of view, as well as high gain to up to 3 keV and still reasonable gain up to 10 keV if the Schmidt arrangement and MFO technology is used. The low weight of both the optic as well as the detector allows considering LE monitors to be flown on small satellites, in extreme case even nanosatellites. These new devices are ready for X-ray astronomy applications and are expected to help solving various questions of the contemporaneous X-ray astrophysics.

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