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Novel space experiments for X-ray astrophysics: LOBSTER EYE

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While the past and recent era of X-ray astronomy was dominated by imaging X-ray telescopes of Wolter type with fine angular resolution but limited field of view (typically less than 1 degree), the wide-field experiments based on Lobster Eye optics are expected to play an increasing role in the future. In this contribution, the capabilities of the considered space mission LOBSTER based on CubeSat 16U with wide-field Lobster Eye optics for investigating celestial X-ray sources are discussed along with recent technological progress. We also show the results of the tests of the quality image in various parts of the field of the lobster-eye telescope prototype.

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1. Introduction

This paper aims to discuss the capabilities of the considered space mission LOBSTER for investigating celestial X-ray sources along with the recent technological progress. As a very wide-field soft X-ray monitor, LOBSTER will be able to provide dense monitoring of the light changes of celestial sources in X-rays. It can be a promising satellite to provide a sensitive X-ray monitor, able to investigate a little-studied long-term activity of various types of celestial objects in the X-ray band.

Here we mean LOBSTER as microsatellite spacecraft payload for prompt observation of transient astrophysical objects in X-ray energy range (Daniel et al., 2022). By combining telescope concepts and miniaturized detectors, the small spacecraft will be able to probe the X-ray temporal emissions of bright events such as Gamma-Ray Bursts (GRBs), X-ray transients or the electromagnetic counterparts of Gravitational Wave Events (GWEs), but also short and long term observations of other types of variable X-ray sources. The spacecraft is based on the CubeSat nanosatellite platform with a volume of 16U.

2. X-ray Sky Surveys and Monitors

Most of the past and recent X-ray telescopes used a narrow field of view (FOV) (less than 1 degree diameter). Albeit some of them e.g. ROSAT (Voges et al., 1999) and eROSITA (Brunner 2022) performed sky surveys, these were limited by the small FOV of Wolter-type optics. Past really wide-field X-ray surveys were hence primarily based on non-imaging experiments/monitors (without the use of optics), hence they were of limited sensitivity. Monitors are typically sensitive to the radiation within energy $2\,\mathrm{keV} < E < 10\,\mathrm{keV}$; hence the soft X-ray emission components often remain unstudied.

ASM/RXTE (All Sky Monitor onboard Rossi X-ray Timing Explorer) (Levine et al. 1996) was a non-imaging instrument operating between 1996 and 2012. Several exposures of a given object per day are available in some cases (but in many cases, only the daily means are meaningful). The sensitivity of RXTE ASM was good for X-ray binaries with the accreting neutron star or the black hole. However, only very few CVs (about 10) were detectable near the sensitivity limit. A new-generation X-ray ASM monitor is needed for X-ray astrophysics.

3. Justification for X-ray sky monitoring

Celestial X-ray sources represent very active objects, with often violent long-term activity in both the optical and X-ray bands outbursts, high/low state transition), and often with rapid transitions between the states of activity. A search for the relation between optical and X-ray activity is essential, as monitoring a large number of celestial X-ray sources is necessary to catch them in various states of activity. Most up to now, X-ray observations of X-ray sources are represented by snapshots catching selected objects in a particular activity state. In most cases, the transitions between the states are not mapped.

There are only poor phenomena and objects statistics (deeper studies are available only for a few targets). It is obvious that the progress in future X-ray sky monitoring, as described briefly in this paper, can yield new valuable data to understand the physical processes in the unpredictable activity (e.g., state transitions) of cosmic X-ray sources in more detail.

The X-ray monitors onboard a given satellite could operate only for a limited time segment. Moreover, the spectral regions differ for the individual monitors; hence it is difficult and sometimes unreliable to combine the data from various monitors. It is necessary to be cautious in assembling a long series of X-ray data from various X-ray telescopes. Most X-ray monitors are sensitive only to the hard or medium X-rays, and very few monitors worked at energies $E < 1$ keV. Many pieces of information need to be included (especially supersoft X-ray sources (a special CV type)) may not be detected at all in the hard X-ray band, although they can be very luminous).

4. Lobster-Eye (LE)

Lobster-Eye Telescopes represent the novel Wide Field X-ray Telescopes with field-of-view (FOV) of about 100 sq. deg. (the classical X-ray optics has only 1 deg or less). The LE telescopes are based on a real analogy with the lobster eyes. They were designed for astronomy, but laboratory applications are also possible. The Lobster Eye (LE) X-ray optics was initially proposed by Schmidt (1975) and Angel (1979). Since then, numerous test specimens of LE telescopes have been designed and tested (e.g., Inneman et al. 1999; Hudec et al. 2000, 2003, 2004; Tichý et al. 2009, 2011). The LE X-ray telescope can be miniaturized for application in picosatellites. The LE telescopes can typically serve in two basic operation modes as follows:

- (a) starring (pointed) mode - only for the satellite with pointing
- (b) scanning mode (no satellite pointing and/or stabilization are required)

The parameters of the LE optics are as follows. The energy range from the optical to the energy of 10 keV in 2D and from the optical to the energy of 30 keV in 1D mode, FOV typical 5×5 deg 1 module, more modules with have a larger FOV, angular resolution 1 to 10 arcmin typical, the gain 100–1000. The application areas are as follows: X-ray astronomy in scanning mode, sky monitoring for transients, X-ray astronomy in pointed mode, dense long-term monitoring of selected sky area, XRF planetary science, X-ray imaging in the laboratory, X-ray laboratory collimators, X-ray imaging of laboratory plasma, X-ray security screening and material research, X-ray imaging and low-resolution spectroscopy of triggers in the atmosphere (balloon experiments), X-ray imaging and low-resolution spectroscopy of polar lights (balloon and rocket experiments).

5. Space LE experiments and projects

5.1 LE in space

- (i) Beppi Colombo Mercury mission (no astrophysics) 2018 operation at Mercury from year 2026.
- (ii) VZLUSAT1 test flight, cubesat, 2016–2023 (Baca et al. 2016, Urban et al. 2017, Baca et al. 2018).

- (iii) REX test flight, rocket 2018.
- (iv) Chinese Einstein test satellite LEIA 2022 Chinese LE optics and CMOS: The Lobster Eye Imager for Astronomy Onboard the SATech-01 Satellite.

5.2 LE in preparation

- (i) ESA THESEUS in preparation-study ESA M7 mission candidate (Amati 2023).
- (ii) ESA-CAS SMILE collaboration with China approved ESA S mission, launch 2024/25.
- (iii) Einstein Probe (EP) is an X-ray mission of the Chinese Academy of Sciences (CAS) due for launch in late 2023. It has the LE Wide-field X-ray Telescope (WXT) onboard.
- (iv) SVOM/MXT – The Space Variable Objects Monitor is a planned small X-ray telescope satellite under development by China National Space Administration, Chinese Academy of Sciences and the French Space Agency, to be launched in March 2024.

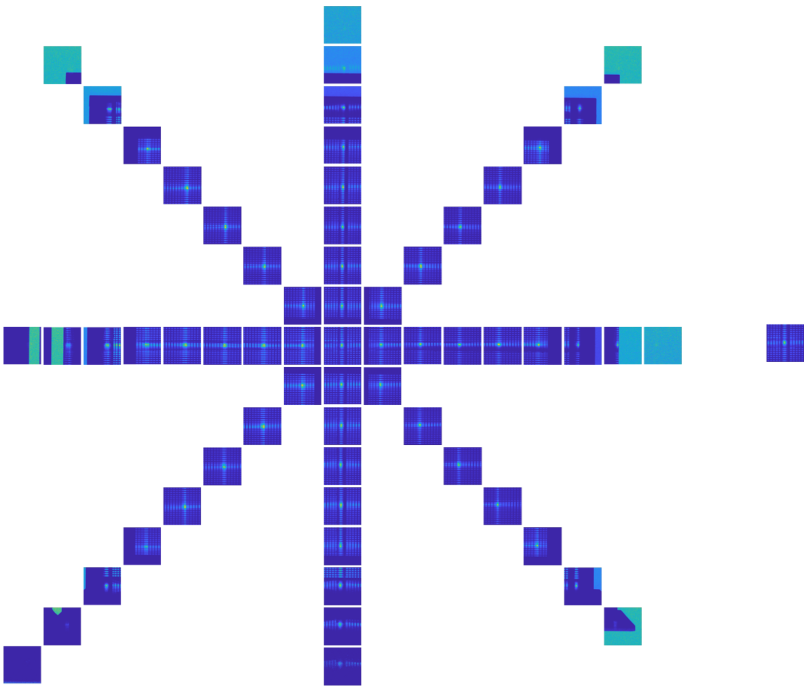

Figure 1: FOV of 2D optics, Ti target, Timepix detector, step 0.5 deg, tests at the Prague VZLU X-ray facility.

6. Science objectives of X-ray monitoring

Wide field X-ray monitors of the Lobster-Eye type were demonstrated to play an essential role in modern astrophysics (e.g., Hudec et al. 2007; Švéda et al. 2004). The most important scientific cases for a monitor are the observations of the activity of the sources in the direction

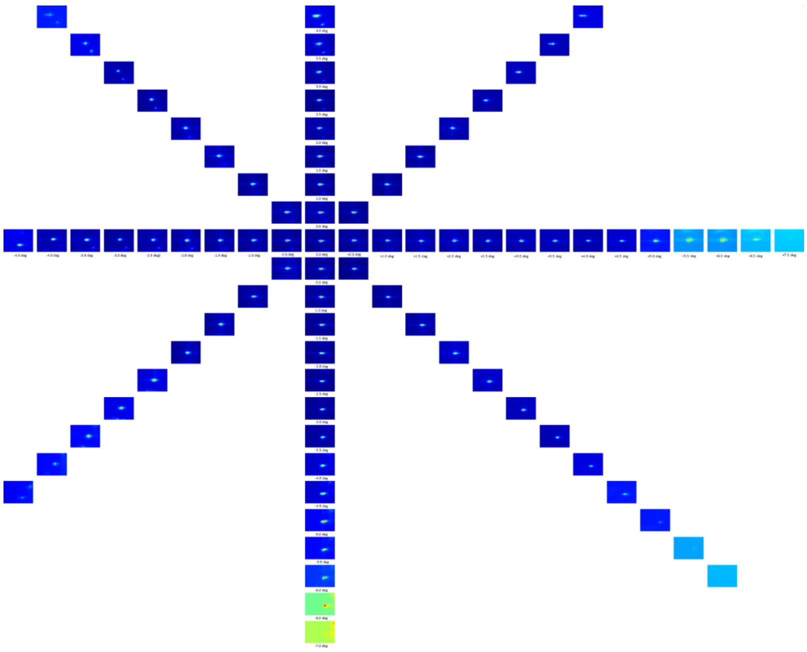

Figure 2: FOV of 2D optics, Ag target, Rigaku CCD camera, step 0.5 deg, tests at the VZLU facility. The demonstrated FOV is 8x8 deg at 3keV.

towards the Galaxy center where these sources are accumulated. We plan to concentrate on the long-term (months) measurements of the light curves of bright, persistent X-ray binaries and also the detection and measurement of the activity of bright transient events in X-ray binaries in the soft X-ray band.

The recently developed and tested LE optics modules in Multi Foil Schmidt arrangement developed in collaboration with Rigaku Prague have demonstrated the large field of view (FOV) of an order of 8 deg x 8 deg (See Figs. 1 and 2).

The related test setup is illustrated in Fig.3.

Both SMILE and THESEUS missions have Czech participation on the main consortium level and payload contribution. Both missions are with SXI soft X-ray telescope with Lobster Eye type optics (Angel arrangement, MCP, Univ Leicester UK).

7. Conclusions

LE-based LOBSTER missions, if approved for space flight, will significantly contribute to the X-ray astrophysics. Extending the observing range to very soft X-rays is important. First LE X-ray telescopes are already in space – including tests, and technology verification. Additional experiments are in preparation: LE (SXI) ESA CAS SMILE, Einstein Probe. There are also proposed space projects with wide field Lobster Optics: BRITE X, THESEUS.

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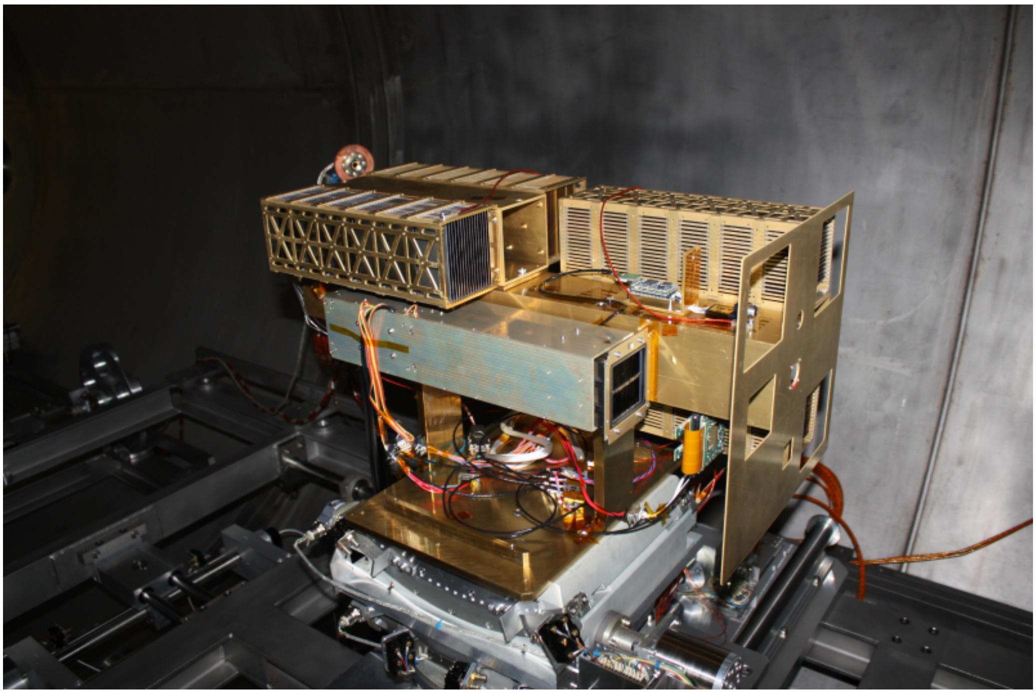

Figure 3: LE optics – X-ray tests at the X-ray test facility Panter (130 m long), one setup for LE and KB optics. The demonstrator include all optical payload (2D LE optic, Quad detector Advacam and Ketek spectrometer)

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