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Novel X-ray imaging instrumentation for astrophysics

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The recent progress in innovative X-ray imaging instrumentation for astrophysics is briefly discussed. The capabilities of the novel instrumentation for investigating celestial X-ray sources are also discussed, along with recent technological progress. We have developed and tested advanced novel Kirkpatrick Baez, Lobster-Eye (LE), and Hybrid X-ray optics mirror technologies, including the calibration and testing of the ongoing developments of this optic. We presented the possibilities of monitoring the objects in the Galactic center region in the soft X-ray energy band by a small LE telescope on a CubeSat-like satellite platform. Even some instruments not designed for astronomy are suitable for investigating the X-ray activity of cosmic sources. E.g., a Soft X-ray Imager (SXI) (LE telescope observing in a soft X-ray band) onboard the ESA-CAS satellite SMILE (designed for X-ray imaging of solar wind Charge eXchange of the magnetosheath and the cusps) is also essential for astrophysics because it is able to provide wide-field imaging of the sky in the soft X-ray region and can be used for investigating the activity of cosmic X-ray sources.

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1. Introduction

In this contribution, we present and discuss a few selected aspects of recent developments and achievements in the field of novel X-ray instrumentation for astrophysics, focusing on wide-field telescopes and monitors.

2. Lobster-Eye (LE) as X-ray wide-field telescopes and monitors

Lobster-Eye Telescopes represent the novel Wide Field X-ray Telescopes with field of view (FOV) of about 100 sq. deg. (the classical Wolter type X-ray optics have only 1 deg or less). They represent an analogy with lobster eyes and were designed for astronomy, but laboratory applications are also possible. The Lobster Eye (LE) X-ray optics were originally proposed by [21] and [1]. Since then, numerous test specimens of Lobster Eye telescopes have been designed and tested (e.g., [13, 9, 10, 7, 26, 27]). The LE X-ray telescope can be miniaturized for an application in picosatellites.

The LE telescopes can typically serve in two basic operation modes as follows: (a) starrying (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 typicaly 5×5 deg 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).

3. Science objectives of X-ray monitors

Wide field X-ray monitors of LE type were demonstrated to play an important role in modern astrophysics (e.g., [8, 25]). The most important scientific cases for a monitor are the observations of the activity of the sources in the direction 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 the detection and measurement of the activity of bright transient events in X-ray binaries in the soft X-ray band.

4. LE telescopes in space – recent news

There was essential progress in applying LE telescopes and monitors onboard satellites and space probes over a few years. Beppi Colombo Mercury mission (no astrophysics) was launched in 2018; there was a VZLUSAT1 test flight, cubesat, 2016–2023, REX test flight, onboard rocket 2018, Chinese Einstein test satellite LEIA 2022 Chinese LE optics and CMOS: The Lobster Eye Imager for Astronomy Onboard the SATech-01 Satellite.

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The most important achievement is the satellite Einstein Probe China, launched on 9 January 2024, at 07:03 UTC, by a Long March 2C rocket from the Xichang Satellite Launch Centre in China.

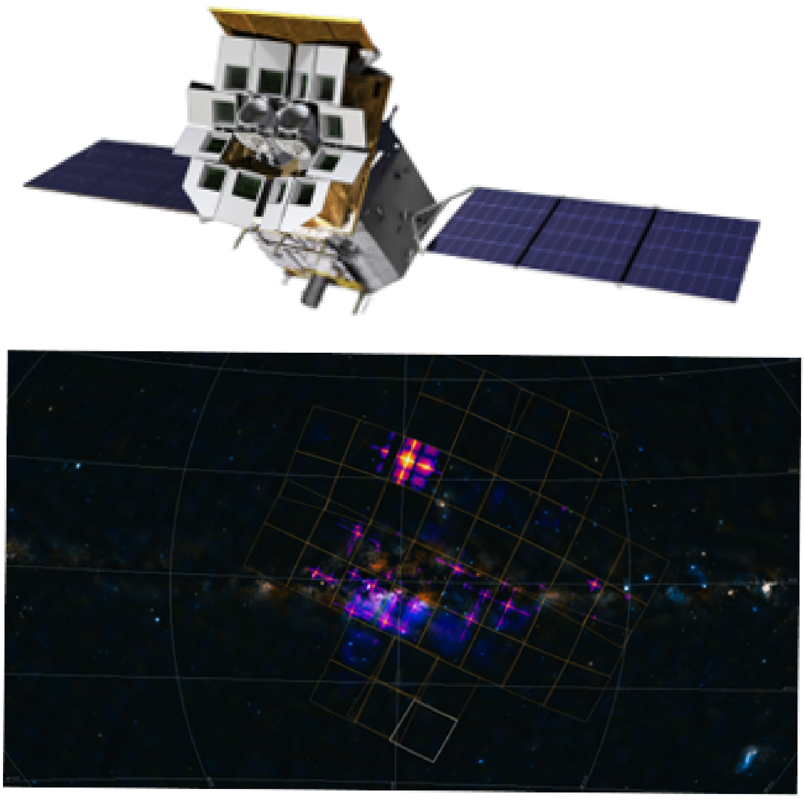

Figure 1: Einstein Probe satellite (upper panel) and the X-ray image captured (bottom panel). Image credit: EPSC, NAO/CAS; DSS; ESO (WXT's X-ray sources are identified in purple, overlaid with the DSS color image provided by ESO. X-ray data credit goes to the EPSC, while ESO credits the DSS data.)

Figure 1 shows the image captured by WXT directed at the center of the Milky Way galaxy for around 40,000 seconds. WXT's lobster-eye optics highlight almost all bright X-ray sources, with cruciform-shaped spots identified in purple and the blue cloud-like structures portraying the emission of foreground hot gas surrounding the galaxy. WXT has the largest FOV, capable of instant imaging nearly 1/11th of the entire sky.

5. LE in space – in preparation and development

There is an ESA THESEUS mission with SXI telescopes with LE optics in preparation-study ESA M7 mission candidate, with a final decision in mid-2026. Another mission is the ESA-CAS SMILE collaboration with China, approved ESA S mission, with an expected launch in 2025.

These missions involve 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).

6. Recently developed innovative X-ray imaging modules

There was significant progress in the design and development of novel X-ray optics of LE and Kirkpatrick Baez (KB) type based on Multi Foil Optics (MFO) Arrangement in the last five years. We have developed and tested advanced novel KB, LE, and special combined X-ray optics mirror technologies, including the calibration and testing of the ongoing developments of this optic. Detailed simulations of novel X-ray optics are necessary to predict the in-orbit and ground-based (finite source distance or parallel beam) performance (i.e., the point spread function and efficiency) of newly developed prototype optics with improved parameters. The designed optics were tested at PANTER and other X-ray and optical test facilities. The work included two basic parts as described below.

1. KB X-Ray optics. We have simulated, designed, assembled, and tested the first advanced modules in KB arrangement. These modules were based on stacked (a) high-quality glass foils and (2) superior-quality silicon wafers. The work included the selection and detailed analyses of the best substrates available.

Such superior substrates may increase significantly the performance of the newly developed modules, with emphasis on improvement of FWHM, improvement of effective area, and extending the energy range.

2. Lobster Eye Optics in Schmidt arrangement. We have simulated, designed, assembled and tested the first advanced modules in the LE Schmidt arrangement as illustrated in Fig. 2 and Fig. 3. These modules were based on (a) high-quality glass foils and (b) superior-quality silicon wafers.

We note that KB-based lenses, as well as various types of LE optics, serve as an example of advanced future X-ray telescopes. Analogously to Wolter lenses, all these systems use the principle that the X-rays are reflected twice to create focal images. Future projects in X-ray astronomy and astrophysics will require large optics with wide fields of view. Large KB modules and LE X-ray telescopes may serve as solutions as these can offer innovations such as wide fields of view (FOV), low mass and reduced costs.

7. Galactic center

We showed in our recent paper [23] the LE monitor's perspectives and observing plan based on a small LE telescope on a CubeSat-like satellite platform. This instrument is able to provide wide-field X-ray imaging. We presented the possibilities of monitoring the Galactic center region in the soft X-ray energy band. Many X-ray binaries, especially those with a low-mass lobe-filling secondary (donor) and mostly the neutron star, concentrate in the bulge surrounding the center of our Galaxy as illustrated in Fig.4.

Several such binaries can be present in our monitor's field of view, a square of about 5×5 degrees. Such monitoring can follow the long-term activity of X-ray binaries located in this region. The remarkable features of such objects' long-term X-ray activity (e.g., outbursts and state transitions) can be detected. Observing in the soft X-ray band is the most promising because their X-ray intensity is the highest in this band.

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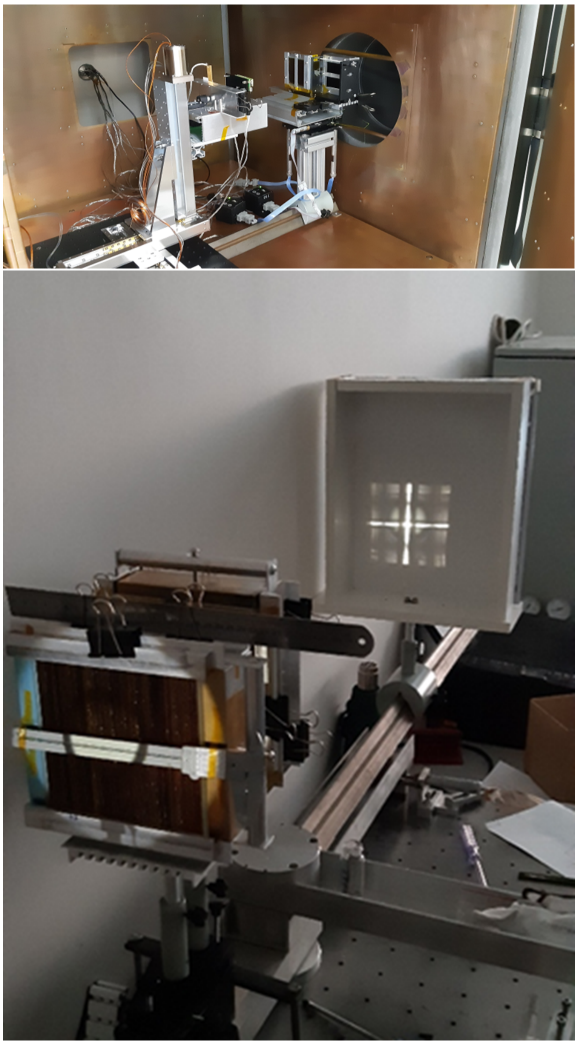

Figure 2: LE test modules at the X-ray test facility and in visible light tests. Photo courtesy RITE Prague.

8. Secondary science for SMILE SXI

Even some instruments not designed for astronomy are suitable for investigating the X-ray activity of cosmic sources. Recently [24], we showed the scientific potential of a Soft X-ray Imager (SXI) (LE telescope observing in a soft X-ray band (0.15–2.5 keV [22]) onboard the ESA-CAS satellite SMILE for investigating cosmic X-ray sources of various types. This telescope, albeit designed for X-ray imaging of solar wind Charge eXchange of the magnetosheath and the cusps, is also essential for astrophysics because it is able to provide wide-field imaging of the sky in the soft X-ray region.

Especially the compact sources like neutron stars accreting matter located in the planned fields (often containing the Magellanic Clouds and their surroundings) to be observed by SXI are promising for detecting and monitoring their long-term activity. Even outbursts in soft X-ray transients will likely be detected, and their time evolution can be investigated.

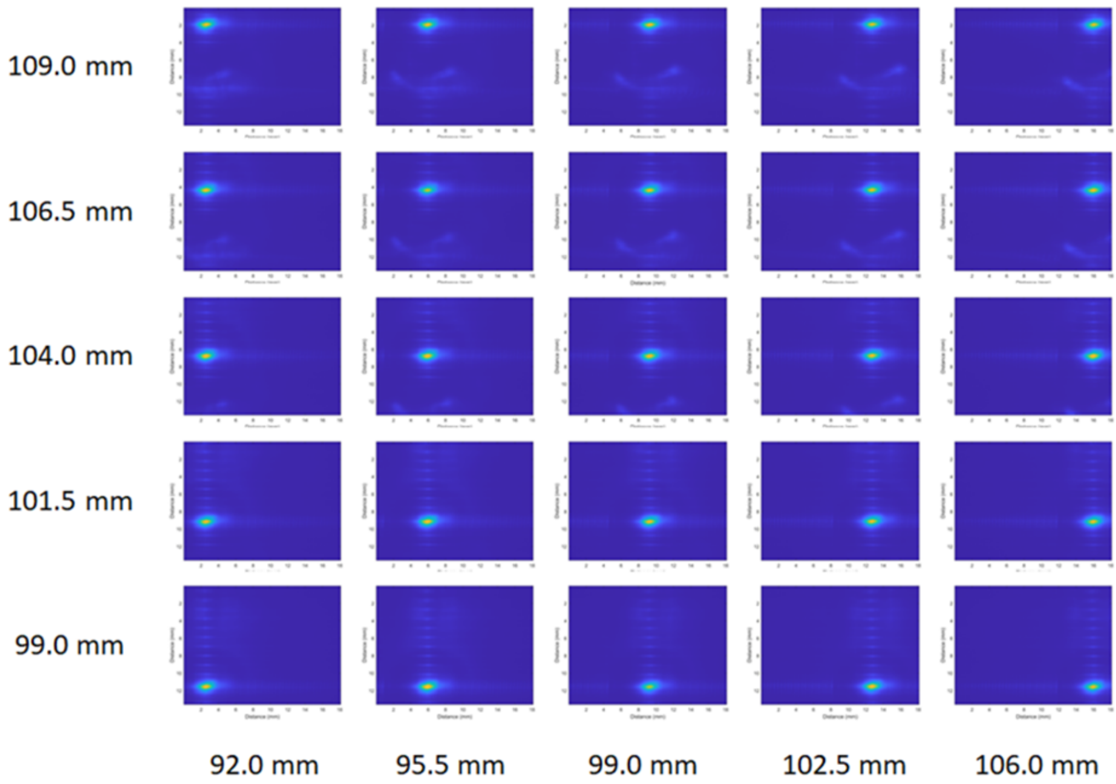

Figure 3: Off-axis behavior of f 400 mm LE module, aperture 69x69 mm, X-ray tests. The detector has a field of view of 2473 × 3297 pixels, which corresponds to a physical area of 17.96 × 13.52 mm. Each of the small pictures represents the area of the detector. Picture courtesy RITE Prague.

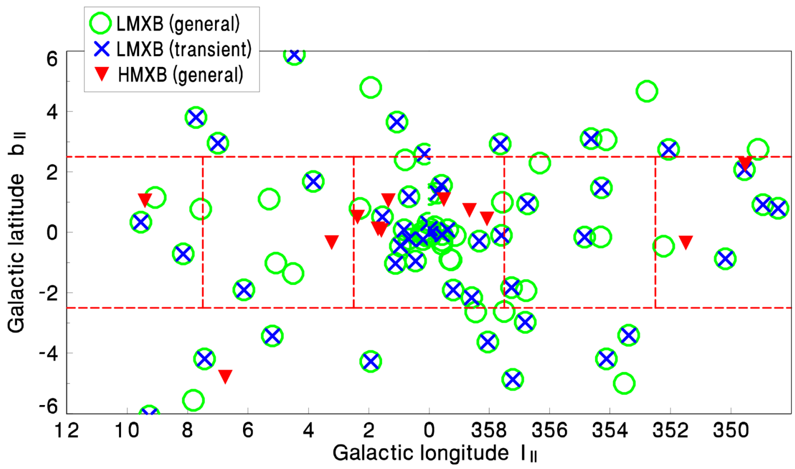

Figure 4: Galactic center monitoring by a wide field LE X-ray instrument. LMXB refers to a low-mass X-ray binary. HMXB denotes a high-mass X-ray binary. A belt in which most such known X-ray objects are located is displayed. Especially LMXBs accumulate around the center of the Galaxy. The direction toward the Galaxy center is in the center of the plot. The data from the catalogs by [15] and [16] were used. The solid lines (squares of 5 × 5 degrees) mark the planned field of view of the proposed LE telescope. Adapted from [23].

9. Conclusions

LE-based LOBSTER missions will significantly contribute to the X-ray astrophysics. LE X-ray telescopes are already in space, and more are in development and/or planned. SMILE SXI, designed for X-ray imaging of solar wind interaction with the magnetosheath and the cusps, is also essential for astrophysics. SMILE SXI is able to provide wide-field (26×15 degrees) imaging of the sky in the soft X-ray region. Outbursts of transient sources (not known when in quiescence) will also be detectable.

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, Einstein Probe serves as an excellent example. Additional experiments are being prepared such as LE (SXI) ESA CAS SMILE and ESA THESEUS. There are also proposed space projects with wide-field LE optics e.g. BRITE X.

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