Contrib. Astron. Obs. Skalnaté Pleso **48**, 456 – 465, (2018)

Lobster Eye X–ray optics for astrophysics: Recent status

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Received: December 16, 2017; Accepted: March 8, 2018

Abstract. X-ray optics in Lobster Eye arrangement represent promising complementary device to narrow field X–ray optics in common use. We present briefly recent status of design, developments, and tests of X–ray optics including Lobster Eye modules developed and tested within recent space project.

Key words: X–ray optics – X–ray telescopes – X–ray astrophysics

1. Introduction

X–ray optics in Lobster Eye (LE) arrangement represent promising complementary device to narrow field X–ray optics in common use. The wide field of view lobster telescope can e.g. detect and provide positions for fast, short lived transients such as gamma–ray bursts and X–rays accompanying gravitational waves, while the narrow field of view Wolter telescope provides high resolution images but can only point to known sources that have been discovered and positioned by other instruments such as the lobster telescope.

We present review of the recent status of design, simulations, development, assembly and tests of Lobster Eye X–ray optics including the modules developed and tested within the recent space projects. Various LE test modules were simulated, designed, assembled and tested at several X–ray test facilities. Selected results are briefly presented and discussed below.

2. Wide–Field Lobster Eye X-Ray Optics

The Lobster Eye (LE) optics mimic the arrangements of eyes of lobsters and was suggested in the 1970s for a very wide field X-ray imaging but used in space only very recently mostly due to severe manufacturing problems. Recently, advanced modules are available for both the Schmidt (Schmidt, 1975) and the alternative Angel (Angel, 1979) configurations, suitable for space applications.

Images in the eye of a lobster are formed through reflections off the internal walls of a lattice of small square-sided tubes arranged over the surface of a sphere. This design can be used in the construction of a grazing incidence system to focus X-rays.

The X-ray objective based on the lobster eye was proposed by (Angel, 1979), and similar design of a wide-field lens by (Schmidt, 1975). Each small channel is aligned along the radius of a sphere. A ray reflected twice off adjacent walls inside the channel is focused onto a spherical focal plane. Rays reflected only once are focused to a line causing background images to appear as a tapered cross. Some rays go through the lens with no reflections, contributing to diffuse background. The finite size of the tubes produces specific defocusing in the image, while the angle subtended by each tube at the focus limits the resolution of the system.

Despite these drawbacks, the great advantage of this design is an almost unlimited field of (Gorenstein, 1979; Gorenstein et al., 1996). This makes it ideal for use as an all-sky X–ray monitor. Up to 2017, no X–ray telescopes were launched using lobster-eye optics, mainly due to difficulty in manufacturing of the reflective tubes. However, improvements in multichannel plate technology has led to a proposal for a lobster-eye X-ray telescope could be placed on the International Space Station, and to an application on BeppiColombo (Fraser et al., 2010), and the alternative glass foil technology developed in the Czech Republic has lead to the construction of several first LE telescopes (Inneman et al., 1999, 2000). These efforts in the Czech Republic have started soon after announcing the idea of lobster optics (Hudec et al., 1995). The first LE module in space is the 1D LE optics on the VZLUSAT–1 minisatellite (Urban et al., 2017), see the dedicated section below.

The wide-field mirror modules offer advantageous application in astrophysics. The major scientific achievements of the X–ray astronomy in the past are closely related to the use of large X-ray imaging telescopes based mostly on the Wolter I X–ray objectives. These systems usually achieve excellent angular resolution as

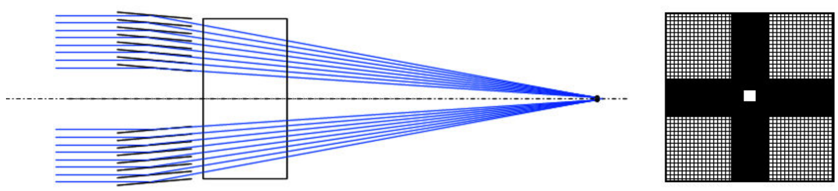

Figure 1.: LE 2D optics – composed of two 1D sub-modules, 2 reflections, energy range optical to 10 keV.

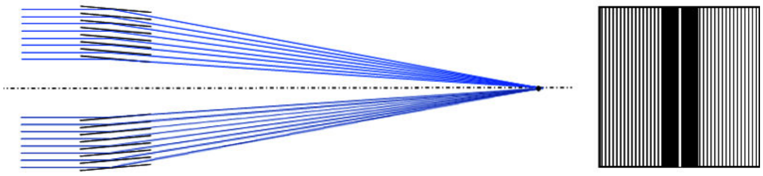

Figure 2.: LE 1D optics – 1 reflection, energy range optical to 30 keV.

well as very high sensitivity, but are quite limited in the field of view available, which is less than 1 degree in most cases. However, 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 wide field lobster eye telescopes are hence expected to play an important role in future X–ray astrophysics missions and analyses.

The 2D LE optical system is illustrated on Fig. 1. For some applications where wider energy coverage (extension to harder X–rays) is necessary, the 1D LE system can be considered (Fig. 2). The imaging properties of these systems in optical light are documented in Fig. 3.

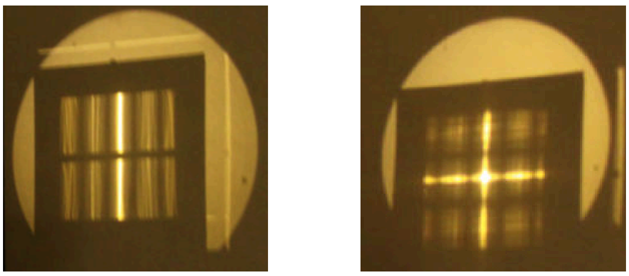

Figure 3.: LE system – test in visible light, left 1D, right 2D.

3. Simulations

For every Lobster Eye test module developed and assembled, ray–tracing simulations were performed in order to simulate the ideal imaging performance (Fig. 4). Few selected results are given below.

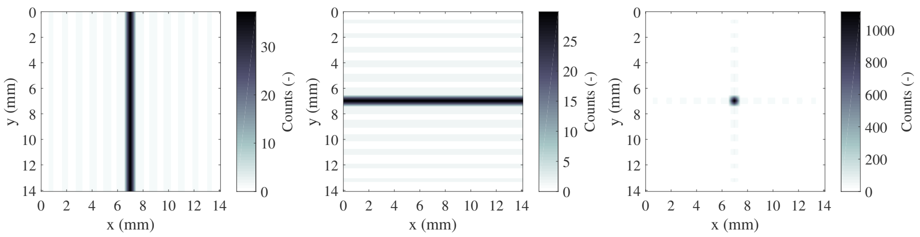

Figure 4.: REX LE optics simulation for source-detector distance 10 m at 8 keV, from left to right two 1D images and combined image.

4. Lobster Eye X–ray optics on VZLUSAT–1

The first LE X–ray optics in space is small Lobster Eye telescope onboard VZLUSAT–1. This cubesatellite represents example of 2U cubesatellite with advanced astrophysical payload onboard (Dániel et al., 2016). One from payloads is represented by one dimensional (Pína et al., 2016) miniature X–ray telescope (Pina et al., 2015) with Timepix detector in its focal plane (Baca et al., 2016). The main mission goal is technological verification of the system but scientific outcome is also expected for bright celestial X–ray sources (Urban et al., 2017; Dániel et al., 2016; Blazek et al., 2017). The satellite represents the 5th satellite with Czech X–ray optics onboard.

The 1D Lobster Eye module onboard VZLUSAT–1 has focal length of 250 mm and is composed of 116 wedges and 56 reflective double-sided gold-plated foils (thickness 145 microns) Input aperture is $29 \times 19\,\mathrm{mm}^2$, outer dimensions are $60 \times 28 \times 31\,\mathrm{mm}^3$. Active part of the foils is 19 mm in width and 60 mm in length and the energy range is 3 to 20 keV. The detailed parameters are documented in Tab. 1 and the pictures of the optics are in Fig. 5.

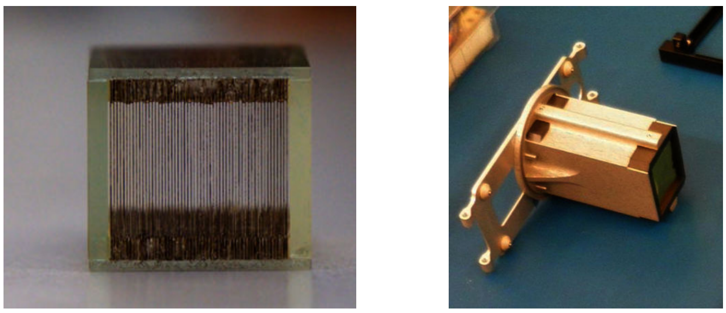

Figure 5.: The 1D LE module for the VZLUSAT–1 minisatellite (left), the 1D LE optics in frame (right).

At the time of writing, the VZLUSAT–1 X-ray payload was still in testing phase. The Timepix detector collects incident X–ray radiation on the satellite and all the electronics and communications of this experiment work well. In consequence of a temporary malfunction the attitude determination and control system (ADCS) and thus caused fast swinging of satellite, it is necessary to capture images with short exposure time. Obtaining images of the source in space is thus distinctively more difficult and statistically improbable. The first image was taken by Timepix on July 13, 2017 and were made more than 20 000 orbital measurements since launch. The results from the satellite operational phase will be presented in consecutive publications.

Table 1.: Parameters of the 1D LE optics for cubesat experiment VZLUSAT–1

Properties	Value
Aperture	$29 \times 19\,\mathrm{mm}^2$
FOV	3.3×2 degrees
Focal length	250 mm
Radius of convergence	500 mm
Dimensions of foils	$60 \times 25 \times 0.145\,\mathrm{mm}^3$
Number of foils	56
Spacing	0.3 mm
Reflective surface	Au
Effective area @ 8 keV and 80 % reflectivity	$\sim 0.5\,\mathrm{cm}^2$
Effective area @ 10 keV and 50 % reflectivity	$\sim 0.3\,\mathrm{cm}^2$
Angular resolution	2 arcmin
Detector	Timepix
Detection material	$300\,\mu$m Si detector
Detector resolution	256×256 pixels
Pixel size	$55\,\mu$m

5. Lobster Eye X–ray optics for rocket experiment

Another LE flight module was designed and manufactured for REX rocket experiment. The goal of this X-ray telescope is the Vela nebula observation during a sounding rocket flight. The Water Recovery X–ray Rocket (WRX–R) experiment is organized by the Pennsylvania State University (PSU), USA with a primary payload of a soft X-ray spectroscope. The Czech team developed a hard X-ray Lobster-eye telescope REX (see Fig. 6; left) as a secondary payload. The Czech experiments astrophysical object of study is the Vela pulsar in the centre of the Vela nebula.

The discussed optics for REX rocket experiment is two dimensional (2D) type. The LE module consists of two sub-modules addressed as Horizontal and

Table 2.: Parameters of the LE optics for rocket experiment REX

Properties	Value
Aperture	$54 \times 54\,\mathrm{mm}^2$
FOV	$1.3{\times}1.6$ degrees
Focal length	1 065 mm
Radius of convergence	2 130 mm
Dimensions of foils	$150 \times 75 \times 0.35\,\mathrm{mm}^3$
Number of foils in one sub–module	47
Spacing	0.75 mm
Reflective surface	Au
Effective area @ 8 keV and 80 % reflectivity	$\sim 1.4\,\mathrm{cm}^2$
Effective area @ 10 keV and 50 % reflectivity	$\sim 0.5\,\mathrm{cm}^2$
Angular resolution	1.1×1.4 arcmin
Detector	Timepix
Detection material	300 μm Si detector
Detector resolution	256×256 pixels
Pixel size	55 μm

Vertical in our case. The Horizontal sub-module is the one with longer focal length, closer to the observed object, which has mirrors oriented horizontally. The Vertical sub-module is placed closer to the camera, with mirrors placed vertically. The final optical system has focal length of 1065 mm and is composed of 114 wedges and 47 reflective single-sided gold-plated foils (thickness 350 microns) in each 1D module. Input aperture is $54 \times 54\,\mathrm{mm}^2$, outer dimensions of one 1D module are $80 \times 80 \times 170\,\mathrm{mm}^3$ and the active part of the foils is 54 mm in width and 150 mm in length. Total energy range is 1 to 15 keV over this energy range it work as soller slit. The main parameters of LE sub-modules are listed in Table 2 and a few selected measurement results are listed in next sections. For more information about the rocket experiment see (Dániel et al., 2017; Stehlikova et al., 2017).

6. X–ray tests at Boulder, Pennstate, Iowa and Prague

Several Lobster Eye modules were assembled and prepared for X–ray tests at the US and Czech test facilities. These LE modules were tested in vacuum chamber at CASA (University of Colorado at Boulder), taking into account the experimental arrangement of the test facility (focus to focus), hence these LE test modules were of focus to focus design, with source to optics distance: 10 m, optics to detector distance: 8 m, module position adjustment in visible light (Xe lamp), and a MCP detector as X–ray focal plane detector, with diameter of 1 inch.

Further X-ray tests were performed at X-ray test facilities in Iowa, Pennstate, and Prague, few selected results are illustrated below. For Pennstate tests, Timepix detector (Jakubek et al., 2014) was used to record the images.

The experimental setup at Pennstate test facility is in Fig. 6, examples of obtained results in Fig. 7. The comparison between simulation and experimental results for Prague measurement of VZLUSAT–1 1D module with used setup schema in Fig. 8 is in Fig. 9.

7. X–ray tests of LE module at PANTER

The full illumination X–ray tests of the LE module designed and assembled for the REX rocket experiment were performed at the Max Planck Institute for Extraterrestrial Physics PANTER facility, Germany in 2017. A few selected preliminary results are shown in Fig. 10. More details on these tests (including other types of X–ray optics) are given in another paper in this Volume (Pina et al., 2018).

8. Conclusions

Various LE X–ray optics modules were assembled and tested, based either on glass foils or high–quality silicon wafers, all of them in multi–foil arrangement, i.e. as stacked modules with flat X–ray reflecting substrates. These modules were tested at several X–ray test facilities, with very promising results, with around 1–2 arcmin FWHM in the best cases.

The LE X–ray optics represent promising alternative to widely used Wolter mirrors, mainly because of much larger FOV albeit at the cost of reduced angular resolution. The LE optics is suitable for use in wide–field X–ray monitors with very wide coverage of various astrophysical sources.

The availability of high-quality novel materials such as superior silicon wafers and/or glass foils enables the design and construction of LE X–ray optical systems with improved angular resolution for various applications both in space,

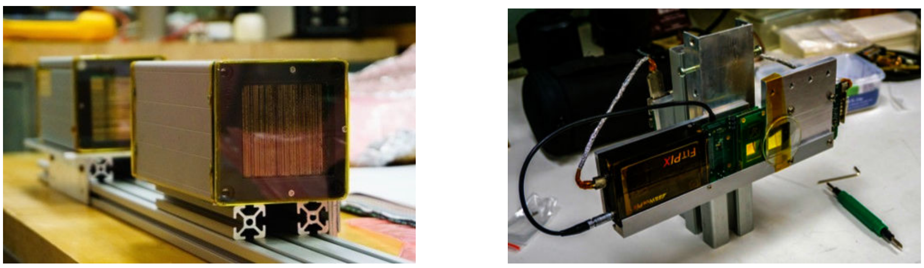

Figure 6.: X–ray tests at the Pennstate X-ray test facility. Left the REX LE module, right the Widepix detector used to record the focal images.

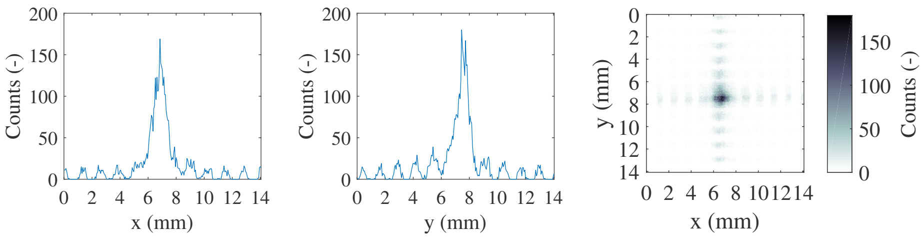

Figure 7.: X-ray tests of the REX LE module at the Pennstate X–ray test facility. The measured FWHM was 1.7 arcmin horizontal and 1.8 arcmin vertical.

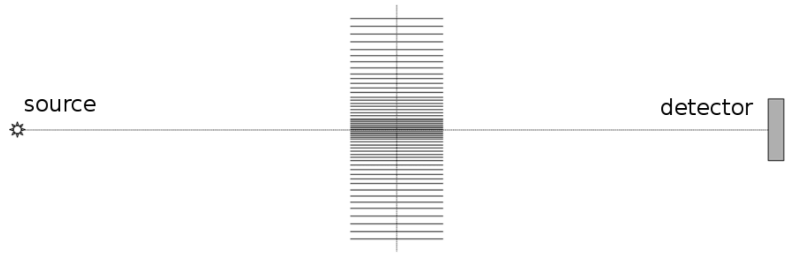

Figure 8.: Hard X–ray tests at RITE Prague, experimental setup. Cu K_α X-ray tube was used as source and Timepix as focal detector. LE optics was placed in the middle between source and detector.

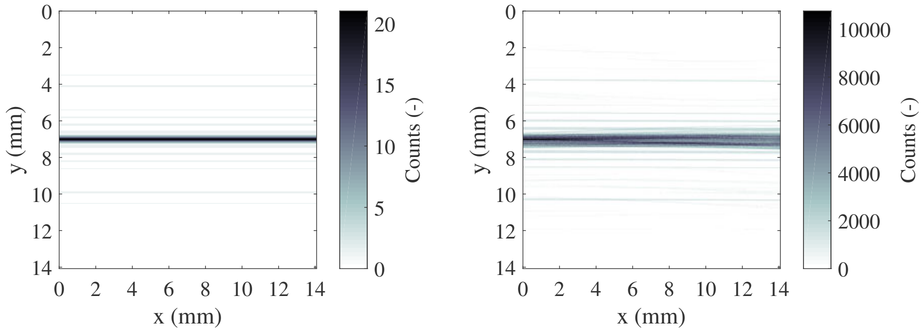

Figure 9.: Experimental tests of 1D LE optics, hard X-rays 8 keV at X–ray laboratory RITE Pregue, left simulated image, right measured image. Source – detector distance was 600 mm, exposure time 0.4 s and maximum signal = 104, after summation 18×105.

astronomy, as well as in the laboratory. In the near future, we plan to continue with assembling and testing LE modules with longer focal length and improved

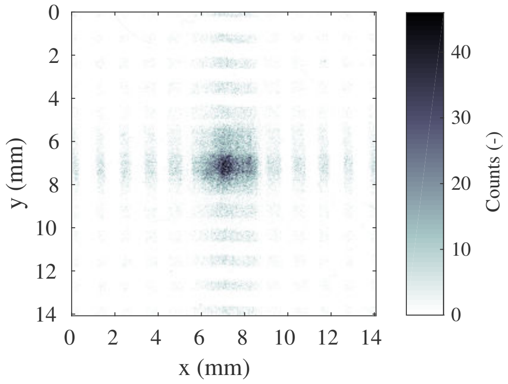

Figure 10.: LE REX PANTER X–ray test results. 2D LE X–ray optics (REX) – image of the 2D focus at 8.04 keV for different focal distance. Best focus in vertical direction 1.21 mm FWHM (1.5 arcmin) and in horizontal direction 0.94 mm (1.3 arcmin).

performance, based on superior quality substrates.

Acknowledgements. We thanks the teams at the X–ray test facilities at Boulder, Pennstate, Iowa and MPE PANTER for their assistance and help with measurements of LE modules there.

We acknowledge GA CR grants 13-33324S, 18-10088Y and AHEAD EU Horizon 2020 project (Integrated Activities in the High Energy Astrophysics Domain), grant agreement n. 654215. This work was partly supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS18/186/OHK3/3T/13 and MEYS RVO 68407700 as well.

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