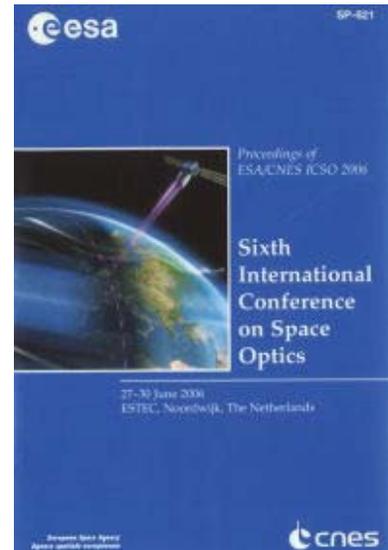


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LOBSTER: new space x-ray telescopes

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LOBSTER: NEW SPACE X-RAY TELESCOPES

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ABSTRACT

The LOBSTER telescopes are based on the optical arrangement of the lobster eye. The main difference from classical X-ray space telescopes in wide use is the very large field of view while the use of optics results in higher efficiency if compared with detectors without optics. Recent innovative technologies have enabled to design, to develop and to test first prototypes. They will provide deep sensitive survey of the sky in X-rays for the first time which is essential for both long-term monitoring of celestial high-energy sources as well as in understanding transient phenomena. The technology is now ready for applications in space.

1. INTRODUCTION

The opening of a new X-ray window to the Universe has significantly contributed to our knowledge in numerous important fields of astronomy and astrophysics. The wide field Lobster Eye telescopes are expected to provide further important contribution and to play an important role in future X-ray astrophysics since they will be able to provide continuous sky monitoring in X-rays with unprecedented sensitivity. The advanced prototypes of Lobster Eye optics modules of various sizes and various arrangements confirm the justification of space applications of these innovative devices.

2. SCHMIDT OBJECTIVES

One dimensional lobster-eye geometry was originally suggested by Schmidt², based upon flat reflectors arranged in a uniform radial pattern around the perimeter of a cylinder of radius R . X-rays from a given direction are focussed to a line on the surface of a cylinder of radius $R/2$. The azimuthal angle is determined directly from the centroid of the focused image. At glancing angle of X-rays of wavelength 1 nm and longer, this device can be used for the focusing of a sizable portion of an intercepted beam of X-ray incident in parallel. Focussing is not perfect and the

image size is finite. On the other hand, this type of focusing device offers a wide field of view, up to maximum of 2π with the coded aperture. It appears practically possible to achieve an angular resolution of the order of one tenth of a degree or better. Two such systems in sequence, with orthogonal stacks of reflectors, form a double-focusing device. Such device offer a field of view of up to 1000 square degrees at a moderate angular resolution.

It is obvious that this type of X-ray wide field telescopes will play an important role in future X-ray astrophysics. The innovative very wide field X-ray telescopes have been suggested based on these optical elements but have not been flown in space so far. One of the early proposals was the All Sky Supernova and Transient Explorer (ASTRE)¹. More recently, the Lobster Eye Optics in Microchannel Plate (MCP) design was considered for the LOBSTER ISS space experiment¹⁹. There is also potential for possible extending the wide field imaging system to higher energy by the use of multilayer or other coatings in analogy to those described for flat reflectors in the Kirkpatrick-Baez geometry¹⁴

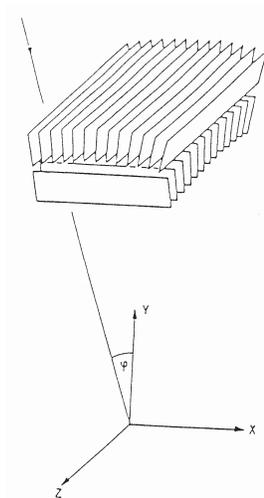


Fig. 1. The Schmidt Lobster Eye objective in the double-focusing arrangement.

3. ANGEL OBJECTIVES

There is also an alternative based on slightly different arrangement, sometimes referred as two-dimensional lobster eye optics. The idea of two dimensional lobster-eye type wide-field X-ray optics was first mentioned by Angel⁴. 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. The field of view can be made as large as desired, and good efficiency can be obtained for photon energies up to 10 keV. Spatial resolution of a few seconds of arc over the full field is possible, in principle, if very small reflecting cells can be fabricated.

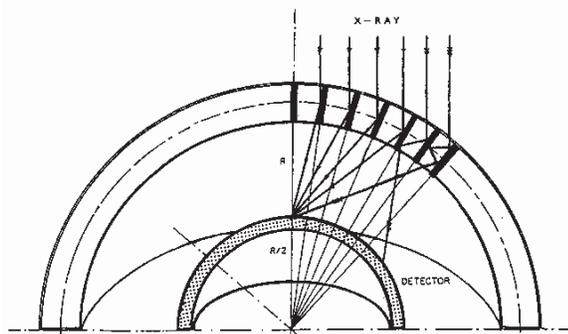


Fig. 2. The schematic arrangement of the Angel lobster-eye objective.

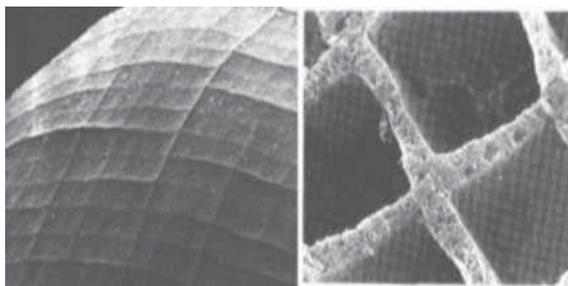


Fig. 3. The eye of a lobster, viewed with a microscope¹⁹. Right: closeup of a small area of the eye. The eye consists of millions of square "channels"; each channel measures approximately 20 microns (or two hundredths of a millimetre) across.

The arrangement described above was however never been further developed because of difficulties with production of numerous polished square cells of very small size (about 1 x 1 mm or smaller at lengths of order of tens of mm). The early feasibility studies have shown that this demand can be also solved by electroformed replication and first test cells as well as

objective laboratory samples have been already successfully developed this way. The recent approach is based on electroforming and composite material technology to produce identical triangular segments with square cells while these segments will be aligned in quadrants onto a sphere.

4. MULTI-FOIL X-RAY OPTICS

There is need for large segmented X-ray telescopes of various geometry and geometrical arrangements including large modules of the Wolter 1 geometry (e.g. assumed for the future ESA X-ray astronomy mission XEUS), large Kirkpatrick-Baez (further referred as K-B) modules (as they can play an important role in future X-ray astronomy projects as a promising and less laborious to produce alternative) as well as large Lobster Eye modules in the Schmidt arrangements. Although these particular X-ray optics modules differ in the geometry of foils/shells arrangements, they do not differ much from the point of the view of the foils/shells production and assembly, and also share all the problems of calculations, design, development, weight constraints, manufacture, assembling, testing, etc.

It is evident that these problems are common and rather important for majority of the large aperture X-ray astronomy space projects. All the space projects require light material alternative. We have developed the various laboratory samples of the above mentioned X-ray optics modules based on high quality X-ray reflecting gold coated float glass foils. The glass represents a promising alternative to recently widely used electroformed nickel shells, the main advantage being much lower specific weight (typically 2.2 g cm^{-3} if compared with 8.8 g cm^{-3} for nickel), however the technology needs to be further exploited and improved in order to achieve the required accuracy. For the large laboratory test modules of dimensions equal or exceeding $30 \times 30 \times 30 \text{ cm}$, mostly glass foils of thickness of 0.75 mm have been used for these large modules, although in future this thickness can be further reduced down to 0.3 mm and perhaps even less (we have successfully designed, developed and tested systems based on glass foils as thin as 30 microns, albeit for much smaller sizes of the modules). The requirement of minimizing the weight of future large X-ray space telescopes and at the same time achieving huge collecting areas means that the future large astronomical mirrors are to be based on thin X-ray reflecting foils i.e. thin layers with low weight which can be easily multiply nested to form the precise high throughput systems. The related novel technologies are discussed elsewhere in this volume²¹.



Fig. 4. The large (30 x 30 x 60 cm) LE 2 D module (0.75 mm thick gold coated glass plates). The array can be re-designed and re-shaped to achieve the approximation of a K-B, or alternatively, of a XEUS (i.e. Wolter) geometry, these modules have been also designed and developed.

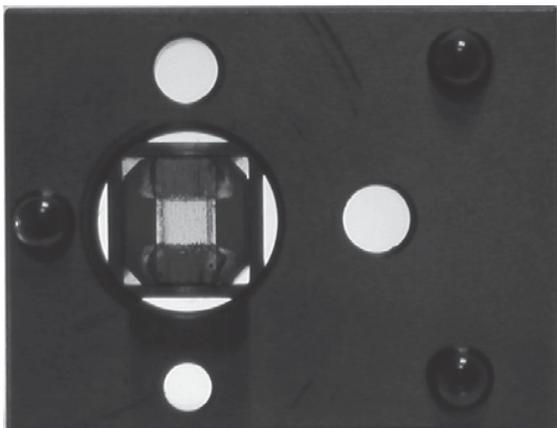


Fig. 5. The micro LE Schmidt module (3 x 3 mm, 0.03 mm thick glass foils) in the holder.

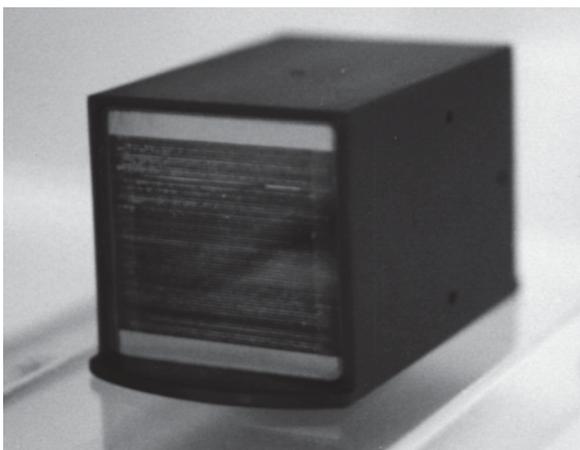


Fig 6. The mini (24 x 24 mm, 0.1 mm thick foils spaced at 0.3 mm) Schmidt LE module illuminated by the laser beam.

5. PROTOTYPES OF LOBSTER X-RAY LENSES

The Lobster Eye Wide Field X-ray telescopes in Schmidt arrangements are based on perpendicular arrays of double-sided X-ray reflecting flats. In the first Lobster lenses developed and tested, double-sided reflecting flats produced by epoxy sandwich technology as well as gold coated glass foils have been used^{12,13}. Micro Schmidt lobster eye arrays with foils thickness as low as 30 microns have been developed and tested in order to confirm the capability of these systems to achieve fine angular resolutions of order of a few arcmin. The thin foils are separated by 50 microns gaps in these prototypes. On the other hand, large lobster eye systems with Schmidt geometry have been designed and constructed, achieving dimensions up to 30 x 30 x 60 cm. Their optical tests have confirmed the expected performance according to calculations (computer ray-tracing). The calculations and the measurement results indicate that the lobster eye telescope based on multiarray of modules with thin and closely spaced glass foils (analogous to those already assembled and tested) can meet the requirements e.g. of the ESA ISS Lobster mission (including the angular resolution and with better transmission) and can hence represent an alternative to the recently suggested MCP technique^{18,19}.



Fig. 7 . The Angel LE linear prototype (47 cells 2.5 x 25.5 mm, 120 mm long).

The large modules of Kirkpatrick-Baez X-ray optics based on multiple and large flats in K-B geometry have been also suggested for future space missions⁷. The K-B modules are based on orthogonal stacks of thin reflectors, each reflector represents a parabola in one dimension. Hence the production technology may be analogous to those developed for Lobster Eye Schmidt lenses. The modular concepts of Schmidt LE modules, of the large segmented Wolter telescopes (such as XEUS), and of large segmented K-B telescopes are similar: all are based on either planparallel or curved flats and foils. This means that the development of high quality X-ray reflecting foils and flats with high mechanical stiffness and low volume density is extremely important for most of the future X-ray astronomy large aperture projects. The segmented K-B telescopes have the advantage of being highly modular

on several levels. All segments are rectangular boxes with the same outer dimensions⁷. The Schmidt LE X-ray lenses developed and tested so far are summarized in the Table 1.

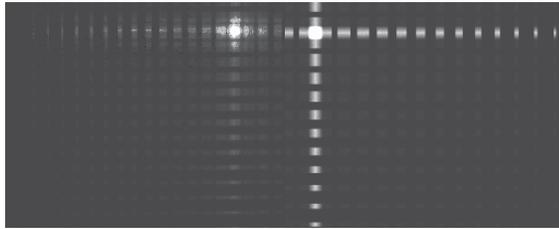


Fig. 8. The experiment (left) and the simulation (right) of the 8 keV point-to-point focusing system. The gain defined as a ratio of the maximum value of the pixel and the value of the directly illuminated pixels is ~570 for the experiment and ~600 for the simulation. The FWHM of both peaks is also close to each other. The focal length of the system is $f = 1.2$ m, the pixel size is $24 \mu\text{m}$ ¹³.

6. SIMULATIONS

In order to be able to make some estimates on the LE performance, image quality, and scanning observation problems, we have developed a ray-tracing code matching our requirements. The first version of our software, currently being operational, works with the set of ideally planar surfaces creating a LE optics. The surfaces has a reflectivity depending on the material and its surface quality. Fully 3-D ray-tracing Monte-Carlo simulations are then performed on such a system. To verify that even such a simple (only planar surfaces) approach can provide us with the valuable results, we have compared the experiment and the simulation of the experiment for the 8 keV photons at point-to-point focusing X-ray LE-like optics. The model fits the experiment quite well (at least from general point of view). There is more sophisticated version of the ray-tracing software under development now, which will be able to deal with the curved and distorted surfaces, as well as with the photon scattering on the micro roughness (angle spread function).

We have performed a number of various LE designs (varying generally in the foil dimensions and the spacing between the foils). One of the promising designs has 78 mm x 23 mm x 0.1 mm foils and spacing between them 0.3 mm. The focal length is $f = 375$ mm. We have simulated the Schmidt LE consisting of these foils coated with the gold with the microroughness $\sigma = 1$ nm.

The gain, defined as the ratio of the photons gathered inside the FWHM area with and without optics, ranges

from ~ 2500 for softer photons (below 2.5 keV) to just several hundreds for harder photons (2.5 – 10 keV). The gain depends on the FWHM, which will be larger in the reality due to the foil distortions, but gain above ~1000 below 2.5 keV can be expected.

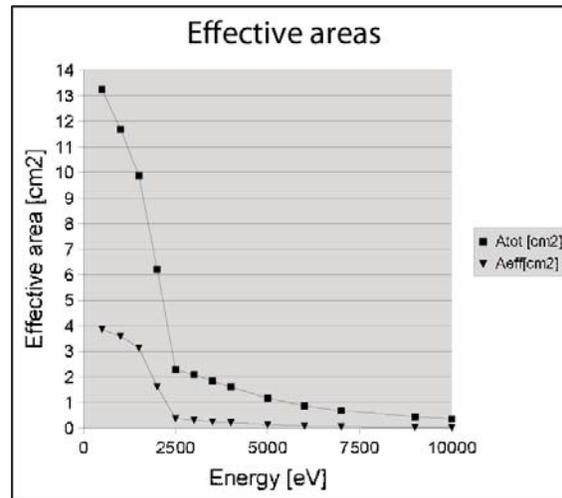


Fig. 9. A_{tot} and A_{eff} for the described optics, note that the front area of the optics is ~60 cm².

The FWHM of a central peak ranges from 2.5 to 4.5 arc min (270 – 480 μm). For most cases the FWHM was below slightly above 3.0 arc min. For real LE the FWHM will be larger, but comparing the model with the experiment show that the blurring will not be immense.

We adopt two definitions of the effective areas¹⁸. First, A_{tot} corresponds with the amount of photons gathered from the single source overall the detector. Second, A_{eff} corresponds with the amount gathered inside the FWHM area. The goal is to minimize A_{tot} while maximizing A_{eff} , e. g. maximize the signal while minimizing the collateral impact on the whole image. A_{eff} is 2-3 cm² below 2 keV and ~0.3 cm² below 7.5 keV. A_{tot} is ~ 3 times larger. The gain, defined as the ratio of the photons gathered inside the FWHM area with and without optics, ranges from ~ 2500 for softer photons (below 2.5 keV) to just several hundreds for harder photons (2.5 – 10 keV). The gain depends on the FWHM, which will be larger in the reality due to the foil distortions, but gain above ~1000 below 2.5 keV can be expected. The FWHM of a central peak ranges from 2.5 to 4.5 arc min (270 – 480 μm). For most cases the FWHM was below slightly above 3.0 arc min. For real LE the FWHM will be larger, but comparing the model with the experiment show that the blurring will not be immense.

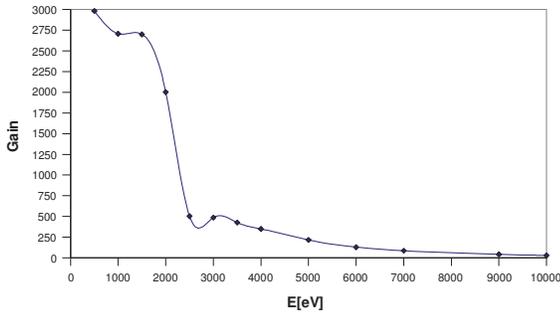


Fig. 10. The gain defined as the ratio of the photons gathered inside the FWHM area with and without optic. Simulation of the LE with 78 mm x 23 mm x 0.1 mm foils and 0.3 mm spacing.

7. THE LOBSTER EYE ALL-SKY MONITOR

The described optics can be used as a soft X-ray All-Sky monitor (ASM). The goal is the monitor sensitive in 0.1 – 10.0 keV range, with the limiting flux $\sim 10^{-12}$ erg/s/cm² in soft X-rays per one day, with the angular resolution ~ 4 arc min and ability to scan almost the all sky several times a day. The proposed ASM will consist of a number of LE modules. Each module will consist of the optics, and the container. The FOV of such a module is 6 x 6 deg. The dimensions of a module are ~ 10 cm x 10 cm x 40 cm. The weight of each module will be 5-10 kg (1 kg the optics, ~ 2 kg the detector, 2-5 kg the container). Each module works independently on the other modules.

The detector in each module can remain planar, although the LE focal surface is curved into a sphere. The image distortion caused by the planar detector is very small for the considered optics. The detector will be ~ 4 cm x 4 cm large with the pixel size of ~ 150 μ m. Fast imaging semiconductor detector seems to be the ideal candidate for this job. Just to mention an example, the EPIC-pn camera onboard the ESA XMM-Newton satellite matches most of the requirements for the detector. But faster detectors based on the MOS technology, currently under development, would be better choice.

If 30 modules are aligned side by side, the total FOV of 180 x 6 deg is available. With the main axis perpendicular to the orbit, the ASM will scan the entire sky once per revolution. The modules can be separated into groups or can be mounted onto the hosting body (satellite, ISS...) completely separately. This is useful to avoid the shielding by other parts of the hosting body. The modularity and module independence provide us with the robustness of the system and decreased development costs. One has to develop and test a single module, while the rest will be completely

the same. The in-situ replacement and/or repair (in case of ISS housing) will quite easy.

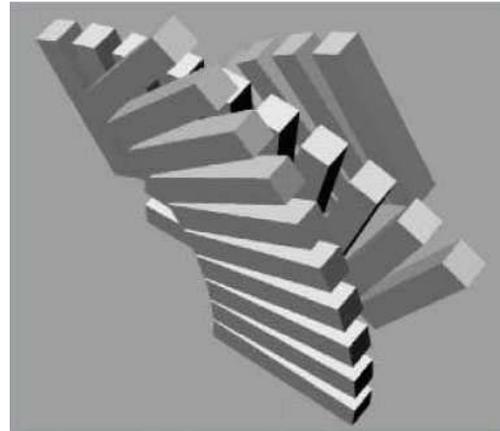


Fig. 11. The example of the module arrangement strategy. All three groups of modules are in the parallel planes.

The average number of events per detector is ~ 6 s⁻¹ (scanning observation simulations based on the 1RXS X-ray source catalogue²⁰, and the background model¹⁸). Each event (photon detection, single pixel event) can be described by 34-38 bits (9+9 position, 12 energy, 4-8 time stamp). Overall 230 bits/s has to be transferred per a single module. Together with the telemetry data, ~ 1 kbit/s is a realistic estimate for average data transfer rate per module.

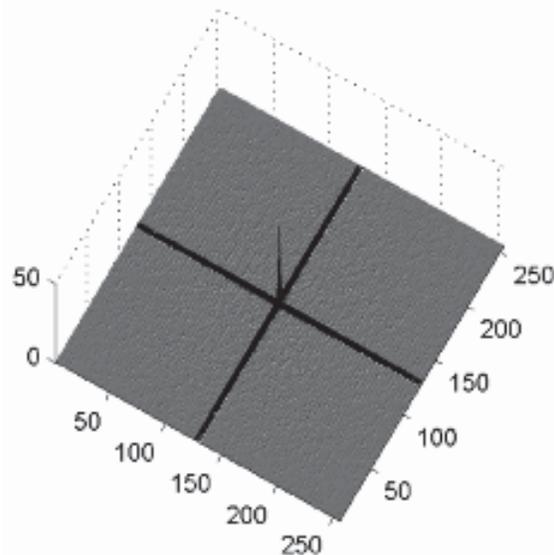


Fig 12. The PSF example for the mentioned optics, pixel size scaled to 2 px/FWHM.

MODULE	size	plate thickness	distance	length	eff. angle	focal length	resolution	field of view	energy
	d(mm)	t(mm)	a(mm)	l(mm)	α	f(mm)	r(arcmin)	(°)	(keV)
macro	300	0.75	10.80	300	0.036	6000	7	16	3
middle	80	0.3	2	80	0.025	400	20	12	2
mini 1	24	0.1	0.3	30	0.01	900	2	5	5
mini 2	24	0.1	0.3	30	0.01	250	6	5	5
micro	3	0.03	0.07	14	0.005	80	4	3	10

Table 1: LE Schmidt modules developed so far

8. CONCLUSIONS

Results of analyses and simulations of lobster-eye X-ray telescopes have indicated that they will 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.

The calculations and the measurement results indicate that the lobster eye telescope based on multiarray of modules with thin and closely spaced glass foils (analogous to those already assembled and tested) can meet the requirements e.g. of the ESA ISS Lobster mission (including the angular resolution and with better transmission) and can hence represent an alternative to the recently suggested MCP technique^{18,19}. 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 sec⁻¹cm⁻² (0.5 to 3 keV) could be obtained, sufficient enough to detect X-ray afterglows of GRBs as well as a rich variety of other variable and transient astrophysical sources.. The various prototypes of both Schmidt as well as Angel arrangements have been produced and tested successfully, demonstrating the possibility to construct these lenses by innovative but feasible technologies. Both very small Schmidt lenses (3 x 3 mm) as well as large lenses (300 x 300 mm) have been developed, constructed, and tested. This makes the proposals for space projects with very wide field lobster eye optics possible.

The recent developments in novel light substrates for precise large space X-ray telescopes²¹ offer possibility to provide very flat foils to be used in Schmidt LE lenses resulting in improved performance of the assembled modules.

Additional application of LE lenses is possible in investigations of X-rays produced in upper atmosphere during tropical storms where LE based experiment could provide wide-field imaging with time resolution of these events. These events are probably related to atmospheric red sprites observed above active

thunderstorms and perhaps even to short gamma ray bursts of terrestrial origin.

ACKNOWLEDGEMENTS

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