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## ALTERNATIVE OPTICS FOR SPACE X-RAY TELESCOPES: FROM LARGE TO SMALL

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### I. INTRODUCTION

The X-ray optics is a key element of space X-ray telescopes, as well as other X-ray imaging instruments. The grazing incidence X-ray lenses represent the important class of X-ray optics. Most of grazing incidence (reflective) X-ray imaging systems used in space applications are based on the Wolter 1 (or modified) arrangement. But there are also other designs and configurations proposed, used and considered for future applications both in space and in laboratory. The Kirkpatrick-Baez (K-B) lenses as well as various types of Lobster-Eye (LE) optics and MCP/Micropore optics serve as an example. Analogously to Wolter lenses, the X-rays are mostly reflected twice in these systems to create focal images. Various future projects in X-ray astronomy and astrophysics will require large segments with multiple thin shells or foils. The large Kirkpatrick-Baez modules, as well as the large Lobster-Eye X-ray telescope modules in Schmidt arrangement may serve as examples. All related space projects will require high quality and light segmented shells (bent or flat foils) with high X-ray reflectivity and excellent mechanical stability. The Multi Foil Optics (MFO) approach represents a promising alternative for both LE and K-B X-ray optical modules. Several types of reflecting substrates may be considered for these applications, with emphasis on thin float glass sheets and, more recently, high quality silicon wafers. This confirms the importance of non-Wolter X-ray optics designs for the future.

In addition to that, some of these X-ray imaging elements/telescopes can be miniaturized, making them suitable for applications in very small satellites including cubesats. Few of these examples will be presented and discussed.

### II. KIRKPATRICK-BAEZ X-RAY OPTICS

Let us briefly introduce and discuss the history of Kirkpatrick-Baez (K-B) systems especially in space use.

The first two-dimensional x-ray image ever obtained in the laboratory with grazing incidence reflection was oriented at right angle to the first one, a point-like focus is achieved. This is true for rays parallel to the centre line of the parabolas. In order to increase the collecting area a stack of parabolas of translation is constructed.

Whereas in the case of only one double plate system a perfect focus for on-axis rays can be achieved this is not possible for a multiple plate arrangement, where the focus remains perfect only along the projected direction of the surface normal of the primary. The exact solution for the intersection point with the focal plane of an arbitrary incident ray is given in the paper [3]. A detailed configurational analysis of the multi-plate Kirkpatrick-Baez system has also been carried out [4].

As for space applications, we note that the Kirkpatrick-Baez (K-B) X-ray optics was actually the first X-ray optics suggested for astronomical use. Despite this fact, albeit some considerations and plans occurred, the astronomical X-ray telescopes flown so far on satellites mostly used the Wolter 1 type optics. Only few historical experiments on sounding rockets used K-B systems. Different situation is in the laboratory where K-B systems are in frequent use e.g. at synchrotrons. The K-B optics, despite suggested for that application, was never flown in a satellite experiment. However, it was used in several rocket experiments in the past, and in addition to that, proposed and discussed for several satellite experiments. In order to increase the collecting area (the frontal area) a stack of parabolas of translation can be constructed for astrophysical applications. However, in contrast to the single double-plate system, the image of a point-like source starts to become increasingly extended in size as the number of plates involved increases. Wolter type I telescopes bend the incident ray direction two times in the same plane, whereas the two bendings in Kirkpatrick-Baez systems occur in two orthogonal planes, which for the same incidence angle on the primary mirror requires a longer telescope [5].

Relatively easy segmentation can also be applied, to the Kirkpatrick-Baez (K-B) array of stacked orthogonal parabolic reflectors. A large K-B mirror can be segmented into rectangular modules of equal size and shape [6].

A segmented K-B telescope has the advantage of being highly modular on several levels. All segments are rectangular boxes with the same outer dimensions. Along a column, the segments are nearly identical and many are interchangeable with each other. All reflectors deviate from flatness only slightly. On the other hand the Wolter reflectors are highly curved in the azimuthal direction and the curvature varies over the mirror.

Although based mostly on glass sheets, there was also a historical attempt to create an astronomical K-B module with silicon wafers [7]. They constructed a test K-B module based on new material/substrate, namely silicon wafers. The telescope module consisted of 94 silicon wafers with diameter of 150 mm, uncoated, with thickness of 0.72 mm. The device was tested both in optical and X-rays, with measured FWHM of 150 arcsecs, dominated by large-scale flatness. It should be noted that the surface quality and flatness of Si wafers improved essentially over the time.

The experimental X-ray astronomy is recently in need of substantial innovations. The recent efforts in design and development future large and precise imaging astronomical X-ray telescopes require to re-consider both the technologies as well as designs. These X-ray telescopes require new light-weight and thin materials/substrates such as glass foils and/or silicon wafers. Their shaping to small radii, as required in Wolter designs, is not an easy task. While the K-B arrangements represent a less laborious and hence less expensive alternative. The use of K-B arrangement for IXO project was suggested and investigated by Marsikova et al. [8], and by Willingale and Spaan [9]. These investigations indicate that if superior quality reflecting plates are used and the focal length is large, angular resolution of order of a few arcsec can be achieved. Recent simulations indicate that in comparison to Wolter arrangement, the K-B optics exhibit reduced on axis collecting area but larger field of view, at comparable angular resolution [9]. Various hybrid systems were also investigated [20].

As for future projects the cost plays an important factor, we note a very important factor and that's is the ease of constructing highly segmented modules based on multiply nested thin reflecting substrates if compared with Wolter design. While e.g. the Wolter design for IXO requires the substrates to be precisely formed with curvatures as small as 0.25 m the alternative K-B arrangement uses almost flat or only slightly bent sheets. Hence the feasibility to construct K-B module with required 5 arcsec FWHM at a affordable cost is higher than those for Wolter arrangement. The advanced K-B telescopes based on Multi Foil Optics (MFO) approach were recently designed and constructed at Rigaku Innovative Technologies Europe (RITE) in Prague based on advanced technologies of shaping of Si substrates have been investigated and developed.

### III. MULTI-FOIL X-RAY AND LOBSTER EYE OPTICS

As already mentioned, there is a 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 ATHENA mission), 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 (LE) 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.

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. For the large laboratory test modules of dimensions equal or exceeding 30 x 30 x 30 cm, mostly glass foils of thickness of 0.75 mm have been used, 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 have 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 [13]. There are also further possible space applications as wide-field X-ray imagers e.g. in planetary and earth and atmospheric science.

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. 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 [12]. 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) [13].

Due to its low weight and small sizes (if suitable small and light-weight detectors are used) the Lobster Eye telescopes represent a suitable payload for micro- and even picosatellites [12]. In extreme cases, the LE telescope can be accommodated inside a 100 x 100 x 300 mm picosatellite [12][13]. Besides astronomical

applications for which the LE telescopes have to be placed onboard satellites [17], there also exist applications in atmosphere science where the LE telescopes should be preferably placed on balloons flying at high altitudes above areas of earth active thunderstorms, to study the related atmospheric X-ray phenomena such as red sprites and/or X-ray emission of terrestrial gamma-ray bursts. Despite the fact that this application was never considered and discussed before, it can provide valuable new scientific results.

Alternative designs can be valuable not only for satellite missions but also for rocket experiments [16].

#### IV. THE NOVEL SUBSTRATES

All the designs and arrangements described above require innovative high quality X-ray reflecting substrates. The glass technology belongs to one of most promising ones, as the volume density of glass is nearly four times less if compared with electroformed nickel layers. The glass foils may be used either as flats, or alternatively may be shaped or thermally slumped to achieve the required geometry [19]. The thermal forming of glass is not a new technology since it has been used in various regions of glass industry and glass art as well as in the production of Cerenkov mirrors. However, the application of this technology in X-ray optics is related with the need to significantly improve the accuracy and minimize the errors. As the first step, small (various sizes typically less than 100 x 100 mm) glass samples of various types provided by various manufacturers have been used and thermally shaped. The geometry was either flat or curved (cylindrical or parabolic) [14]. The project continued with larger samples (up to 300 x 300 mm) and further profiles. The recent efforts focus on optimization of related parameters of both glass material and substrates as well as of the slumping process. The preliminary results show that the quality of the thermal glass replica can be significantly improved by the optimization of the material and design of the mandrel, by the modification of the thermal forming process, as well as by the optimization of the temperature. After the (partly significant) modifications and improvements we have obtained the resulting deviation of the thermally formed glass foil from the ideal designed profile less than 1 micrometer (peak to valley value) in the best case [14]. For near future, we plan continuation of these efforts together with investigations of computer-controlled forming of glass foils (according to the principles of active optics) [15][18].

Another alternative is the use of X-ray optics based on commercially available silicon wafers manufactured mainly for purposes of semiconductor industry. Silicon is relatively light (volume density 2.3 g cm<sup>-3</sup>) and already during the manufacture process it is lapped and polished (either on one or on both sides) to very fine smoothness (better than few 0.1 nm) and thickness homogeneity (of the order of 1 micrometer). Our approach is based on two steps, namely (i) on development of dedicated Si wafers with properties optimized for the use in space X-ray telescopes and (ii) on precise shaping the wafers into optical surfaces. The stacking to achieve nested arrays is performed after the wafers have been shaped. In order to achieve the very high accuracy required by future large space X-ray telescope experiments like ESA ATHENA, the parameters of the Si wafers have to be optimized (for application in X-ray optics) already at the production stage. This is why we have established and developed a multidisciplinary working group including specialists from the development department of Si wafer industry with the goal to design and manufacture Si wafers with improved parameters (mostly flatness) optimized for application in X-ray telescopes. The flatness (in the sense of the deviation of the upper surface of a free standing Si wafer from a plane) of commercially available Si wafers was however found not to be optimal for use in high-quality (order of arcsec angular resolutions) X-ray optics. The most of Si wafers show deviations from the plane of order of few tens of microns. After modifying the technology process during the Si wafer manufacture, we were able to reduce this value to less than few microns. Also the thickness homogeneity was improved about 5 times if compared to standard products [15]. In collaboration with the manufacturer, further steps are planned to improve the flatness (deviation from an ideal plane) and the thickness homogeneity of Si wafers. In addition, the shape accuracy can be essentially improved by application of active optics methods [15].



**Fig. 1** The Mini 2D LE objective with focal length of 250 mm suitable for application in cube and picosatellites. The inside view of the Mini 2D LE module (right).

#### V. MINIATURE LE TELESCOPES AS PAYLOAD FOR MICRO AND PICOSATELLITES

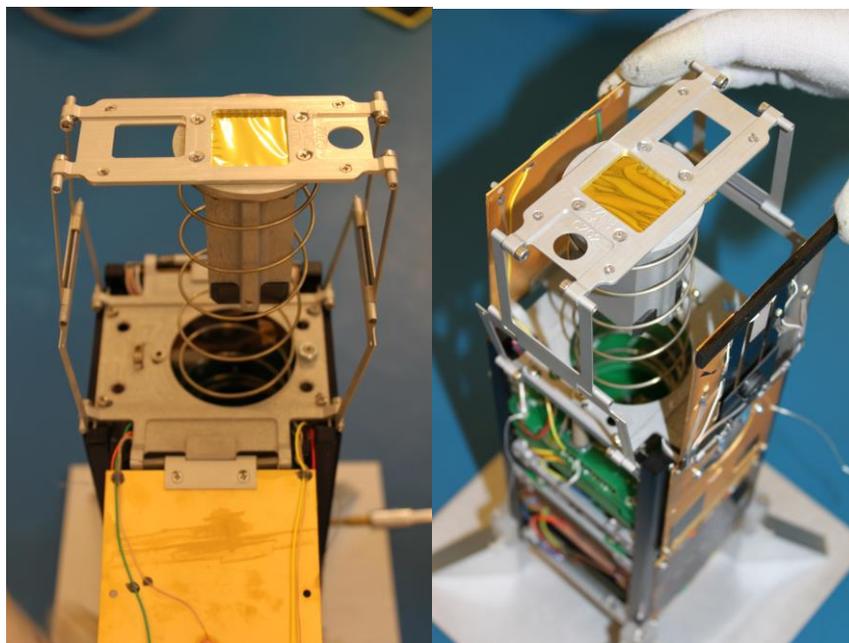
Due to its low weight and small sizes (if suitable small and light-weight detectors are used<sup>22</sup>) the Lobster Eye telescopes represent a suitable payload for micro- and even picosatellites. In extreme cases, the LE telescope can be accommodated inside a 100 x 100 x 300 mm picosatellite.

Recently, miniature LE X ray telescope with 1D LE optics is ready for launch onboard the VZLUSAT1 nanosatellite [21] The 1D LE is more suitable for low X-ray intensities and harder X-rays (5 - 20 keV). For hard X-ray LE works as a Soller slit. Optics above 35 keV behaves as a collimator (Soller slit), so that the gain is only 1. Maximum energy is limited by the Timepix detector. Timepix can be used also for measurement of spectrum of astrophysical objects. This LE X ray monitor has FOV 3deg, Energy range 3-60 keV, Spectral resolution 5 keV, works in Dosimetry mode, Spectral mode, and Photon mode. Silicon pixel detector is used in the focal plane with 256x256 pixels, Pixel size 55 microns, FWHM 20 arcmin @ 4.5keV. Focal length is 250 mm, mass 800 grams and the nanosatellite volume is 2U.

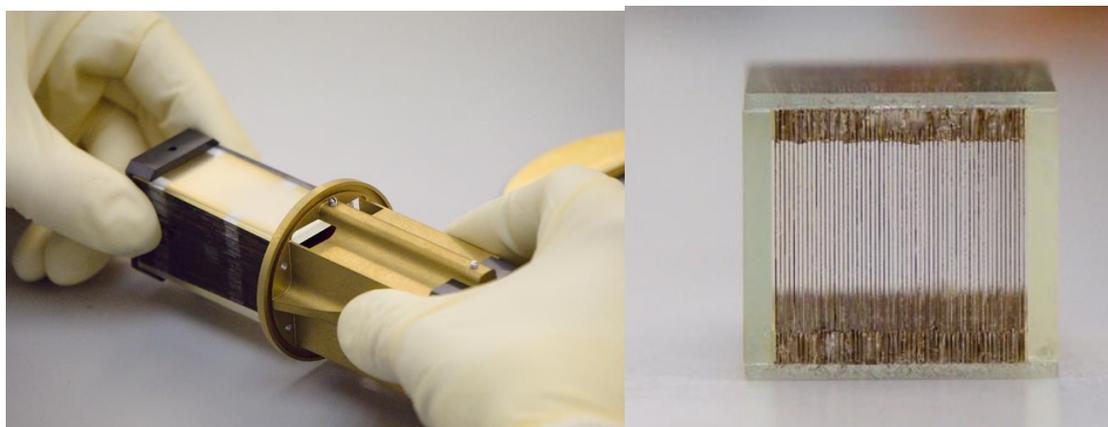
1D Lobster Eye module with focal length 250 mm is composed of 182 wedges and 90 reflective double-sided gold-plated foils (thickness 150  $\mu\text{m}$ . Input aperture: 29 x 19 mm, Active part of the foils: 19 mm in width and 60 mm in length, Outer dimensions: 29 x 31 x 60 mm, Energy range 3 to 20 keV.



**Fig. 2** Imaging properties of the Mini 2D LE system – imaging of the Sun in optical light and The Mini 2D LE module with focal length of 900 mm (right).



**Fig. 3** The Miniature 1D LE telescope on nanosatellite VZLUSAT1..



**Fig. 4** The Miniature 1D LE optics for the nanosatellite VZLUSAT1..

## V. CONCLUSIONS

The K-B and Lobster systems represent a promising alternative to classical imaging X-ray telescopes. The use of novel high quality X-ray reflecting substrates is important for these designs in order to achieve high angular resolution and to reduce the weight. Two promising substrates suitable for future large-aperture and fine resolution X-ray telescopes are glass foils shaped by the Glass Thermal Forming and Si wafers with proper bending. In both cases, promising results have been achieved, with peak to valley deviations of final profiles from the ideal one, being of order of 1 micron in the best cases, with space for further essential improvements and optimization. The principles of active optics can be also implemented [18]. Miniature X-ray optics in Lobster Eye arrangement is suitable for application on cube and picosatellites.

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