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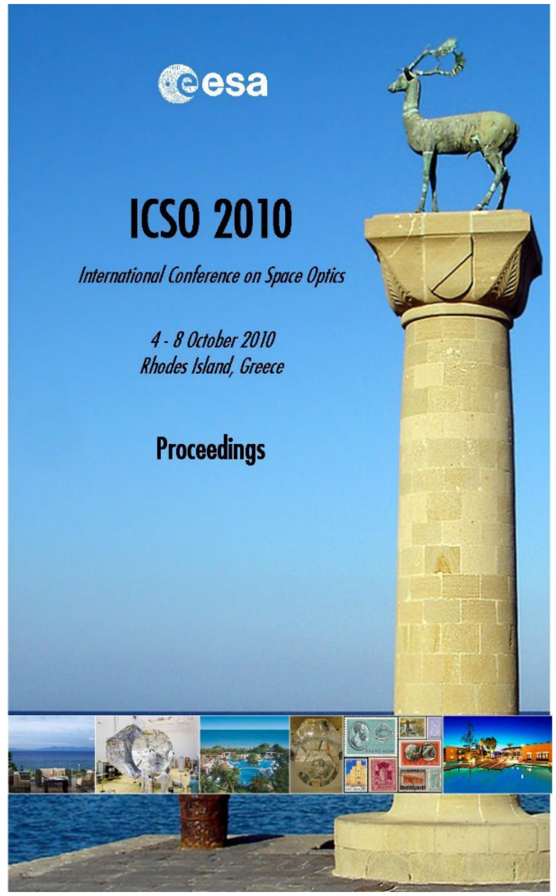

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NEW TRENDS IN SPACE X-RAY OPTICS

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I. INTRODUCTION

The X-ray optics is a key element of various X-ray telescopes, X-ray microscopes, 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 astronomy but also in other (laboratory) 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 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 these 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 represent 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.

Future large space X-ray telescopes (such as IXO) require precise and light-weight X-ray optics based on numerous thin reflecting shells. Novel approaches and advanced technologies are to be exploited and developed. In this contribution, we refer on results of tested X-ray mirror shells produced by glass thermal forming (GTF) and by shaping Si wafers. Both glass foils and Si wafers are commercially available, have excellent surface microroughness of a few 0.1 nm, and low weight (the volume density is 2.5 g cm^{-3} for glass and 2.3 g cm^{-3} for Si). Technologies are needed to be exploited; how to shape these substrates to achieve the required precise X-ray optics geometries without degradations of the fine surface microroughness. Although glass and recently silicon wafers are considered to represent most promising materials for future advanced large aperture space X-ray telescopes, there also exist other alternative materials worth further study such as amorphous metals and glassy carbon [1]. In order to achieve sub-arsec angular resolutions, principles of active optics have to be adopted.

II. KIRKPATRICK-BAEZ X-RAY OPTICS

The first two-dimensional x-ray image ever obtained in the laboratory with grazing incidence reflection was taken by a Kirkpatrick-Baez system [2]. The configuration is shown in Figure 2. The incident rays are focused to a line image by a parabolic sheet mirror. If the rays are reflected a second time from a parabolic surface 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 (Fig. 1). 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].

The Kirkpatrick-Baez (K-B) X-ray optics was actually the first X-ray optics suggested for astronomical use. Despite to 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].

Segmentation can also be applied, to the Kirkpatrick- Baez (K-B) array of stacked orthogonal parabolic reflectors (Figure 1). As shown in Figure 1, 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 a wide range. Furthermore, within a segment, the K-B reflectors themselves can be segmented along the direction of the optical axis. As shown in Figure 1, a K-B mirror system can be folded more easily than the Wolter mirror into a compact volume for launch and deployment in space.

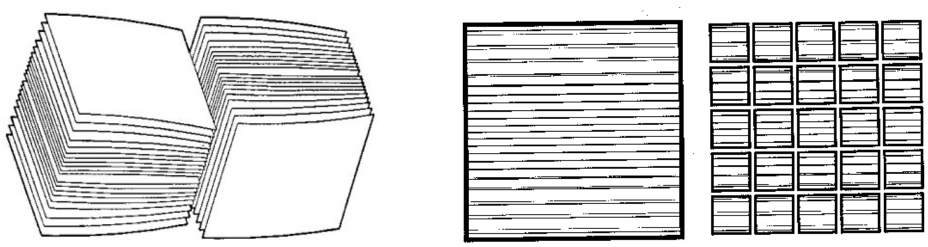


Fig.1: Kirkpatrick-Baez mirror consisting of orthogonal stacks of reflectors (left). Each reflector is a parabola in one dimension [6].A large K-B mirror can be segmented into rectangular modules of equal size and shape [6].

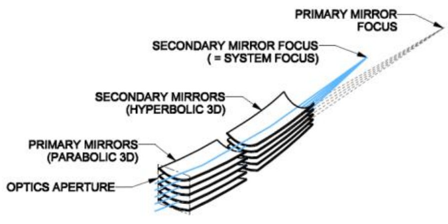
First attempt to create an astronomical K-B module with silicon wafers have been reported in [7]. They constructed a test K-B module based on new material/substrate, namely silicon wafers. The telescope module consisted of 94 silicon wafers with diameter of 150 mm, uncoated, with thickness of 0.72 mm. 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 recent efforts in future larger and precise imaging astronomical X-ray telescopes require to re-consider both the technologies as well as designs. The future large 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 more recently 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].

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:

- Advanced technologies of shaping of Si substrates have been investigated and developed. Suitable substrates for X-ray mirrors are Si wafers because of their parameters.
- Model based on ray-tracing (11 profiles)

- Two sets of mirrors from Si chips 100x100x0.525 mm
- Total optics length 600 mm, aperture 40x40 mm



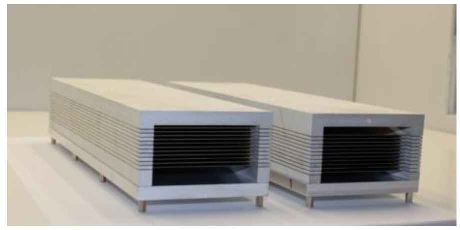


Fig. 2. (left) Principle of K-B MFO telescope Fig. 3. (right) Laboratory samples of advanced K-B MFO modules designed and developed at Rigaku Innovative Technologies Europe (RITE) in Prague.

Table 1: Basic parameters of MFO K-B modules assembled in 2009.

	KB 001	KB 003	KB 004
Shape of substrates:	elliptic	parabolic	elliptic
Focal length [m]:	16	20	16
Aperture [mm]:	100x50	100x50	100x50
Number of profiles:	2	11	2
Number of substrates:	6	33	6
Size of substrates [mm]:	100x100x525	100x100x525	100x100x525
Surface:	Au	Au	Au
Skeleton/House:	Al	Al	Al

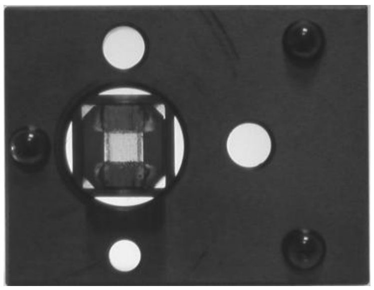
Table 2: Comparison of Wolter and K-B optical arrangement in astronomical X-ray telescope.

	KB	W
Type of optics	Parabolic-parabolic planar	Parabolic-hyperbolic rotational
Number of reflections	2	2
Focal length - Aperture	20 m – 913 x 913 mm 40 m – 1826 x 1826 mm	10 m – dia 913 mm 20 m – dia 1826 mm
First mirror	134 mm from axis 268 mm from axis	134 mm from axis 268 mm from axis
Number of mirrors	420 840	394 788
Length of substrate	300 mm	300 mm
Material substrate	silicon	glass
Surface	gold	gold

III. 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/NASA/JAXA X-ray astronomy mission IXO), 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.

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. 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 atmosphery science.



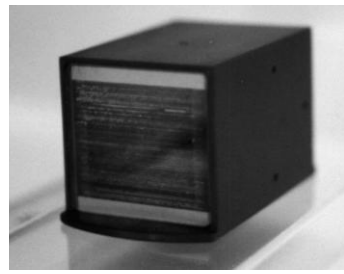


Fig. 4. The micro LE Schmidt module (3 x 3 mm, 0.03 mm thick glass foils) in the holder (left). The mini (24 x 24 mm, 0.1 mm thick foils spaced at 0.3 mm) Schmidt LE module illuminated by the laser beam (right).

A. 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. 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].

B. LE Telescopes as Payload for Micro and Picosatellites and balloons

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]. Beside astronomical applications for which the LE telescopes have to be placed onboard satellites, 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.

IV. THE NOVEL 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. 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].

Another alternative recently considered as one of the most promising, 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^{-3}) 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).

There exists several X-ray optics arrangements with use of Si wafers. Our approach is based on two steps, namely (i) on development if dedicated Si wafers with properties optimised 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/NASA/JAXA IXO, 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 arces 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.

V. CONCLUSIONS

There are new developments in the novel types of astronomical X-ray optics, based on the use of thin X-ray reflective foils. The K-B and Lobster systems represent a promising alternative to classical imaging X-ray telescopes. Two promising substrates suitable for future large-aperture and fine resolution X-ray telescopes have been exploited and investigated in detail, namely the Glass Thermal Forming and Si wafer 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.

VI. ACKNOWLEDGEMENTS

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