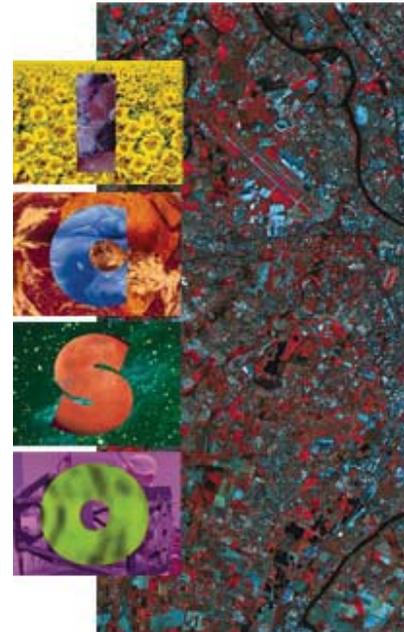


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## *Novel wide-field x-ray optics for space*

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NOVEL WIDE-FIELD X-RAY OPTICS FOR SPACE

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**ABSTRACT** - *We report on the program of design and development of innovative very wide field X-ray optics for space applications. We describe the idea of wide field X-ray optics of the lobster-eye type of both Angel and Schmidt arrangements. This optics was suggested in 70ies but not yet used in space experiment due to severe manufacturing problems. The lobster-eye X-ray optics may achieve up to 180 degrees (diameter) field of view at angular resolution of order of 1 arcmin. We report on various prototypes of lobster-eye X-ray lenses based on alternative technologies (replicated double sided X-ray reflecting flats, float glass, replicated square channels etc.) as well as on their optical and X-ray tests. We also discuss the importance and performance of lobster-eye X-ray telescopes in future X-ray astronomy projects.*

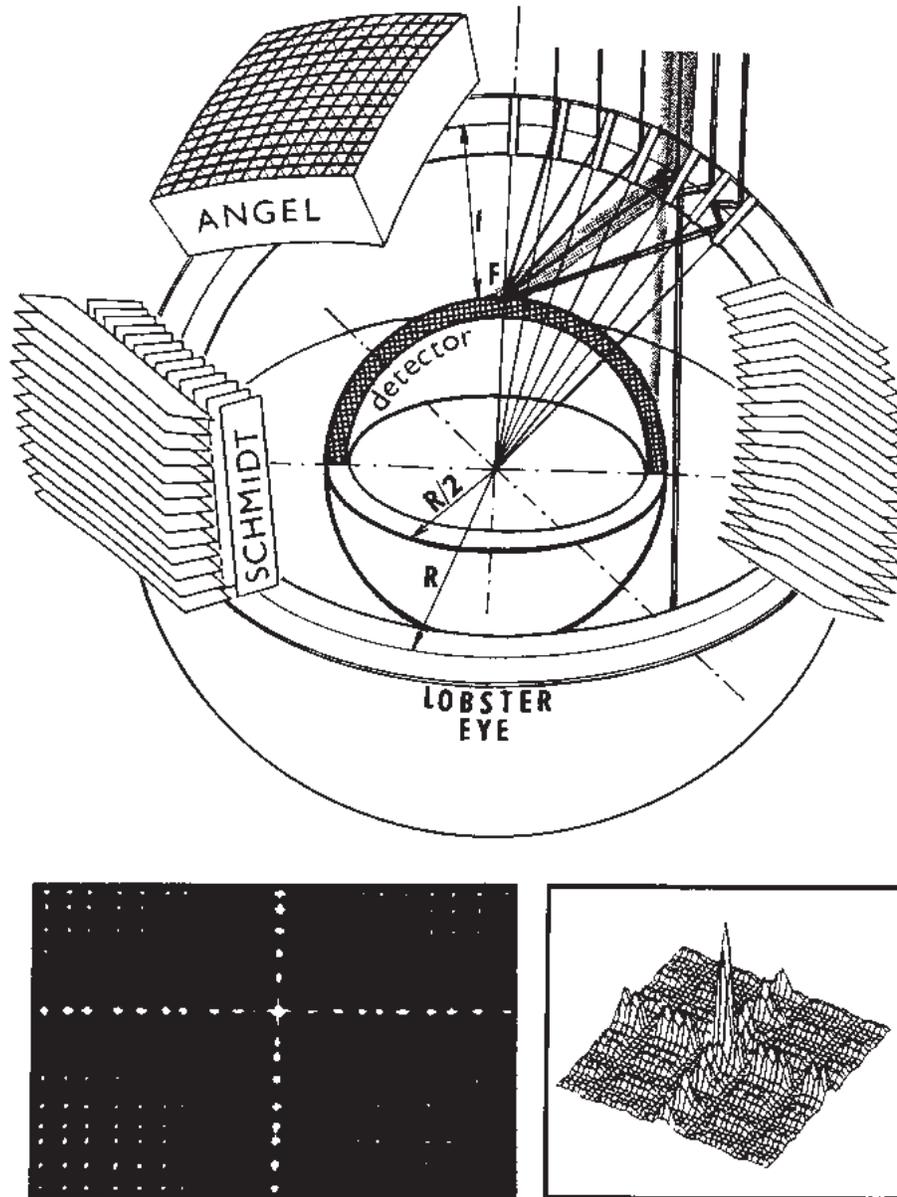
## 1. INTRODUCTION

There are various astrophysical problems requiring sensitive wide-field monitoring of the X-ray sky. However, the imaging X-ray telescopes in current use mostly have limited field of view and the same is valid for new coming missions. The alternative X-ray optics geometries achieving very large fields of view have been theoretically suggested in the 70ies but have been not constructed and used so far.

We review the recent progress of the design and development of wide-field X-ray optical systems based on one- and two-dimensional lobster-eye geometry and suggest technologies for their development and construction. Further results of the development of replicated X-ray reflecting cells for use in two-dimensional X-ray optics of lobster eye type are presented and discussed. The recent developments focus on improved performance of lobster eye test modules, especially increasing angular resolution. This is possible by application of smaller cells and smaller spacing. The wide-field X-ray telescopes of Lobster eye type are expected to play an important role in future X-ray astrophysics missions and projects. The reason is the novel science, which can be approached by these devices including important fields such as Gamma Ray Bursts (GRB). For recently in detail investigated GRB with precise localization accuracy, in almost all cases variable and/or fading X-ray counterparts/afterglows have been identified. The X-ray identification of GRBs has lead to great improvements in study and understanding of these sources and especially has allowed identifications at other wavelengths due to better localization accuracy provided in X-rays if compared with gamma ray observations. Since most of GRBs seem to be accompanied by X-ray emissions, the future systematic monitoring of these X-ray transients/afterglows is extremely

important. However, these counterparts are faint in most cases, hence powerful wide field telescopes are needed. An obvious alternative seems to be the use of wide field X-ray optics allowing the signal/noise ratio to be increased if compared with non-focusing devices. The expected limiting sensitivity of Lobster eye telescopes is roughly  $10^{-12}$  ergcm<sup>-2</sup>s<sup>-1</sup> for daily observation in soft X-ray range [Gore 87]. This is consistent with the fluxes detected for X-ray afterglows of GRBs. Furthermore, the wide field X-ray telescopes may play an important role in monitoring of faint variable X-ray sources to provide better statistics of such objects (note e.g. the occurrence of two faint fading X-ray sources inside the gamma ray box of GRB970616 [Grei 97]) as well as in other fields of X-ray astrophysics.

The lobster-eye geometry X-ray optics offer an excellent opportunity to achieve very wide fields of view while the classical Wolter grazing incidence mirrors are limited by about 1 deg FOV. There are two slightly different arrangements of this type of X-ray lenses.



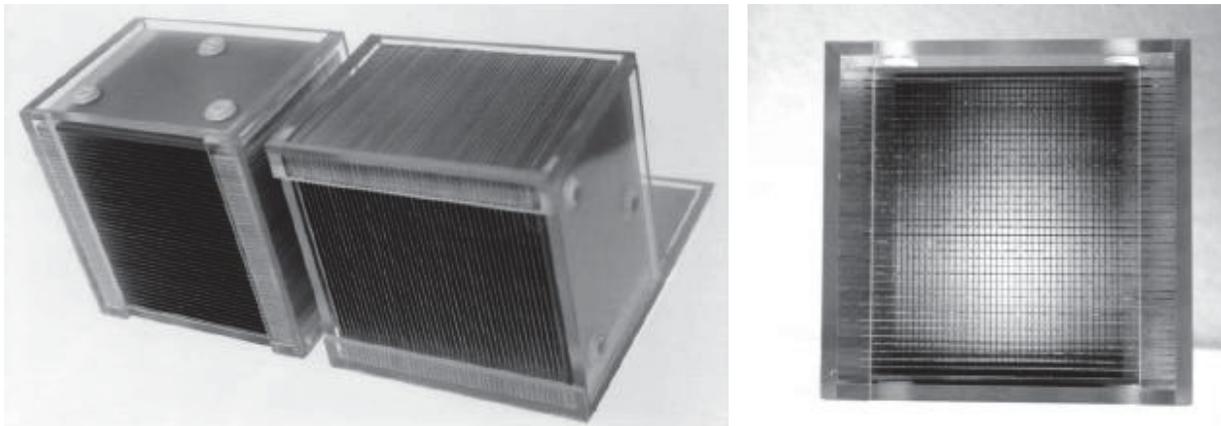
**Fig. 1:** Arrangement of lobster-eye X-ray lenses based on Schmidt and Angel geometry. Bottom left: real optical image of distant point-like source, bottom right: computer ray-tracing for a point-like source.

## 2. SCHMIDT OBJECTIVES

The first type of lobster-eye X-ray lenses is the Schmidt arrangement. Schmidt [Schm 75], based upon flat reflectors, originally suggested one dimensional lobster-eye geometry. The device consists of a set of flat reflecting surfaces. The plane reflectors are arranged in a uniform radial pattern around the perimeter of a cylinder of radius  $R$ . X-rays from a given direction are focused 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. Focusing 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  $2\pi$  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 should offer a field of view of up to 1000 square degrees at moderate angular resolution. It is obvious that this type of X-ray wide field telescopes could 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 proposals is the All Sky Supernova and Transient Explorer (ASTRE) [Gore 87]. This proposal also includes a cylindrical coded aperture outside of the reflectors, which provide angular resolution along the cylinder axis. The coded aperture contains circumferential open slits 1 mm wide in a pseudo-random pattern. The line image is modulated along its length by the coded aperture. The image is cross-correlated with the coded aperture to determine the polar angle of one or more sources. The field of view of this system can be, in principle, up to 360 deg in the azimuthal direction and nearly 90 % of the solid angle in the polar direction.

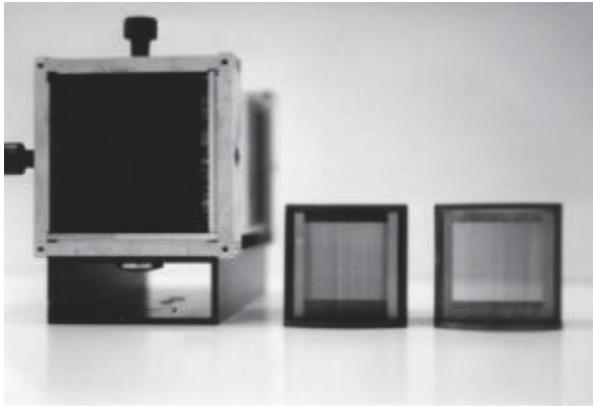


**Fig. 2:** Large Schmidt module based on 80 x 100 mm plates

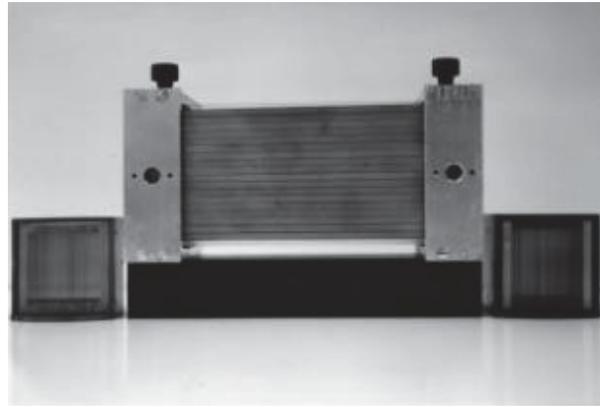
To create this mirror system, a development of double sided flats is necessary while the recent X-ray foils are one-sided in most cases. There is potential for extending the wide field imaging system to higher energy by the use of multilayer coatings in analogy to those described for flat reflectors in the Kirkpatrick-Baez geometry [Joen 94].

First Lobster-eye X-ray Schmidt telescope prototype consisted of two perpendicular arrays of flats (36 and 42 double-sided flats 100 x 80 mm each). The flats were 0.3 mm thick and gold-coated. The focal distance was 400 mm from the midplane. The FOV was about 6.5 degrees. The results of optical and X-ray tests have indicated the performance close to those provided by mathematical

modeling (ray-tracing). The X-rays test of this first prototype have been carried out in the test facility of the X-ray astronomy group, University of Leicester, UK.



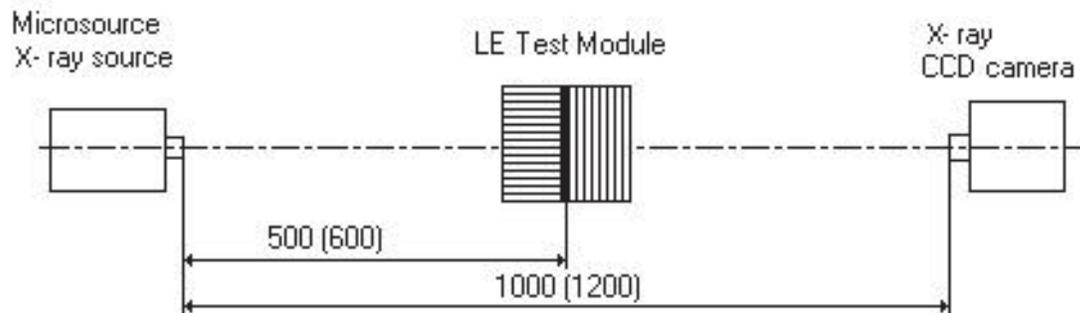
**Fig. 3:** Prototypes of L-shaped Angel (left) and mini (23 x 23 mm plates) Schmidt (right) X-ray telescopes



**Fig. 4:** Bottom view of the Angel telescope

Numerous further test modules of Schmidt arrangement have been developed and tested. In this paper, we want to focus on advanced Schmidt test modules of slightly different geometry and with significantly improved angular resolution.

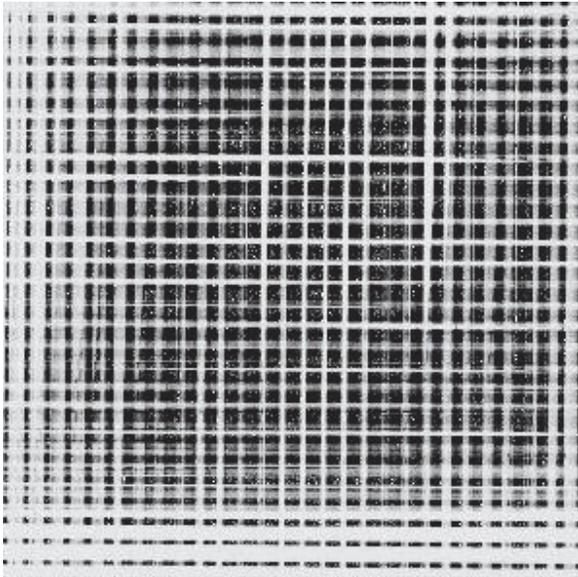
The first advanced test module (further referred as LE) consists of two perpendicular parts. The first part consists of 33 planparallel gold-coated glass flats 100 microns thick spaced at 500 microns. The module has dimensions 17 x 20 x 30 mm. The second advanced part of the module has 50 perpendicular flats 100 microns thick spaced at 0.3 mm with the same dimensions. The flats of the second part are tilted by 3 microns each. The 2D system described above has been tested in X-rays at 8 keV. The test configuration is in Figure 6. The Bede X-ray Microsource has served as a X-ray source, and the Reflex s.r.o. 16 bit X-ray CCD camera as X-ray device capturing the focal image.



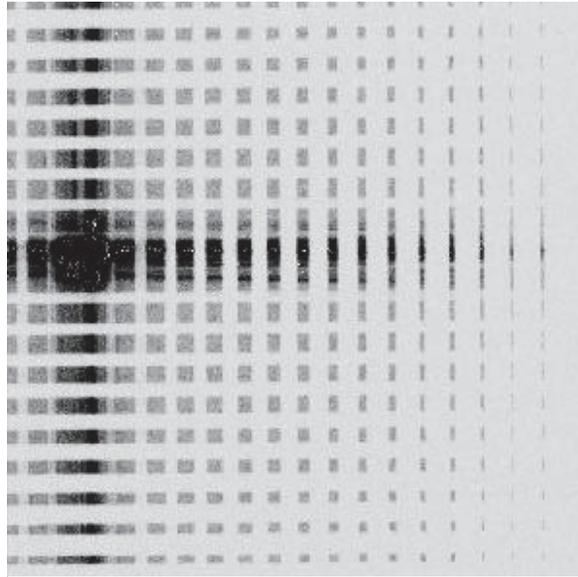
**Fig. 5:** Arrangement of the X-ray tests of the improved Schmidt test module. The indicated measures are in mm.

The second test module (further referred as LES) developed and tested consists of two identical perpendicular arrays of 60 + 60 tilted gold coated glass flats 23 x 25 mm each. The flats are 0.1 mm thick and are spaced at 0.3 mm. They are tilted by 5 microns. The test experiment arrangement was

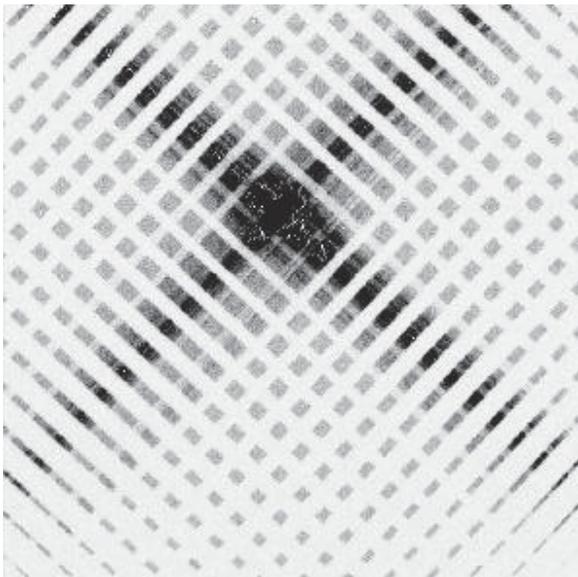
identical as those given in Fig. 6, the only difference being the distance (values given in parentheses are valid for this case).



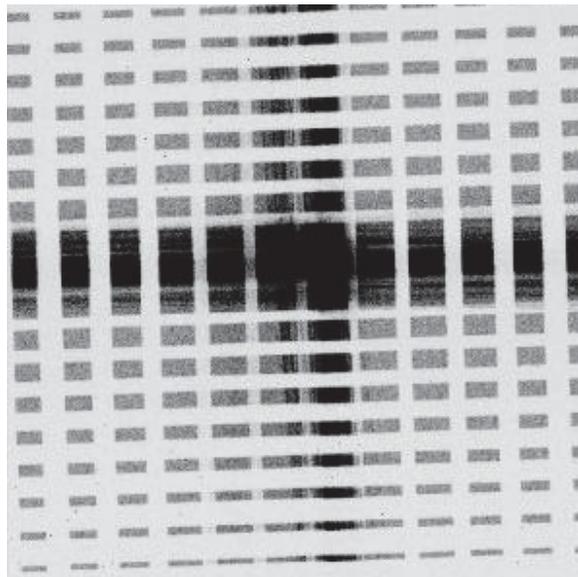
**Fig. 6:** The X-ray shadow gram of the LES module showing the 100 micron thick gold plated flats and approx. 300 (500) micron spaces separating them (and also confirming the high optical quality of used flats).



**Fig. 7:** The X-ray focal image of the LES module showing the main intensity to be inside the main focal spot. The intensity gain achieved is 570 (for 8 keV X-ray tube and only part of the LE module active due to the high energy of X-ray photons – note that this module has been designed for energy of 2 keV).



**Fig. 8:** The LES module X-ray focal spot image, another detector position angle.

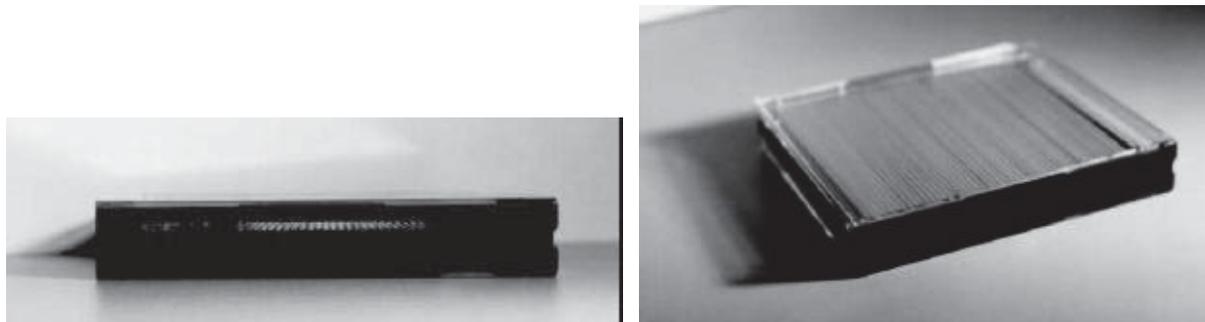


**Fig. 9:** The focal plane image for the LE test module. The measured gain is 500.

All test experiments indicated in the Figures 8 to 21 were done with the microfocuss X-ray tube (Bede Microsource, Cu anode, 40 kV, 100 microamp) and the X-ray CCD Digital Camera (Reflex X16D3, 16bit, DN>30 000, 512x512 pixels, Back Illuminated CCD chip SiTe, direct exposure).

### 3. ANGEL OBJECTIVES

The second modification of the Lobster-Eye optics (sometimes referred as the 2D system) has been also proposed and calculated. The idea of two dimensional lobster-eye type wide-field X-ray optics was first mentioned by Angel [Ange 79]. 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. This idea 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). On the other hand, the very wide field imaging of the sky in X-rays would have very important consequences for a number of applications in X-ray and gamma-ray astronomy and astrophysics. This demand can be also solved by electroformed replication<sup>9</sup> and first test cells as well as objective prototypes have been already successfully developed this way. The recent approach is based on the electroforming and composite material technology to produce identical triangular segments with square cells while these segments will be aligned in quadrants onto a sphere.



**Fig. 10:** Angel telescope linear module

The 1st Angel telescope prototype consists of linear arrangement of 47 square cells of 2.5 x 2.5 mm, 120 mm long (i.e. length/size ratio of almost 50), with focal length of 1.3 m. The 2nd Angel telescope prototype is represented by an array of 6 x 6 i.e. 36 square cells, 2.5 x 2.5 mm each, 120 mm long, focus and length/size ratio as above. Both of these prototype modules have been produced already and are tested recently. The microroughness of the inner reflecting surfaces is better than 1 nm. The modification is the L-shaped module with 2 x 18 cells shown in Fig. 3, 4. The 3rd prototype module is in development, with 96 x 96 = 9216 square cells with length and focus length as indicated above.

### 4. DISCUSSION

The recent achievements of X-ray and Gamma ray astrophysics confirm the needs for high sensitivity wide-field monitoring/imaging experiments. The use of very wide field X-ray imaging system could be without doubts very valuable for many areas of X-ray and gamma ray astrophysics. 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. Limits as faint as  $10^{-12}$  erg cm<sup>-2</sup> s<sup>-1</sup> 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<sup>-1</sup>cm<sup>-2</sup> (0.5 to 3 keV) could be obtained, sufficient enough to detect X-ray afterglows to GRBs.

The production of corresponding optical elements can be reasonably achieved by methods of electroforming and composite replication as an alternative to other methods [Prie 96]. For the Schmidt objectives, the results obtained with the development of technology for production of large area and high quality two-sided X-ray foils [Inne 99] are very promising and together with composite material technologies represent an important input for the development of double-sided flats needed for lobster eye geometries of X-ray optics. The production of Angel lobster eye cells is much more complicated, however the first arrays of the lobster eye Angel cells have been also successfully designed and developed [Hude 00].

The new improved lobster eye X-ray optics prototypes described in this paper confirm the feasibility to design these telescopes achieving fine angular resolution of order of one arcmin with currently available innovative technologies. Nevertheless, the following steps still are to be undertaken for a real wide field X-ray telescope:

1. To further reduce the microroughness as well as the slope errors of the reflecting surfaces in order to further improve the angular resolution and the system reflectivity/efficiency
2. To design and to construct larger or multiple modules in order to achieve larger fields of view (of order of 30 degrees and/or more) and enhanced collecting area
3. For Angel geometry, to further reduce the aperture of the cells and to enhance the length/aperture ratio (recently nearly 50).
4. To study the multilayer (as well as other types of additional layers) application on reflecting surfaces in order to improve the energy coverage for higher energies.

## ACKNOWLEDGEMENTS

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