HIGH–ENERGY ASTROPHYSICS WITH LOBSTER

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ABSTRACT

This paper deals with astrophysical and technological aspects of innovative very wide–field X–ray telescopes with high sensitivity still maintaining good angular resolution. The prototypes designed, developed and tested by the authors are very promising, allowing the proposals for space projects with very wide–field Lobster–eye X–ray optics to be considered for the first time. The novel telescopes will monitor the sky with unprecedented sensitivity and angular resolution of order of 1 arcmin. They are expected to contribute essentially to study of various astrophysical objects such as AGN, SNe, Gamma-ray bursts (GRBs), X–ray flashes (XRFs), galactic binary sources, stars, CVs, X-ray novae, various transient sources, etc. For example, the Lobster optics based X-ray All Sky Monitor is capable to detect around 20 GRBs and 8 XRFs yearly and this will surely significantly contribute to the related science.

INTRODUCTION

On contrary to the visible sky, the X–ray sky as seen by astronomical X–ray telescopes is highly variable, rich in variable and transient sources of both galactic as well as extragalactic origin. Among physically most important transient sources, the detection of Gamma Ray Bursts (GRBs) in X-rays confirms the feasibility of monitoring, detecting and study of these phenomena by their X-ray emission (either prompt or afterglow, e.g. Amati et al., [1] and Fontera et al., [5]). For classical GRBs, the X–ray afterglows are detected in $\sim$ 90 % of the cases (De Pasquale et al., [3]). Moreover, there are X-ray rich GRBs, (hypothetical) orphan GRBs (detectable in X-rays but not in gamma-rays due to different beaming angle) and XRFs which can be detected and studied in X-rays. However, since these events cannot be predicted, and are relatively rare, very wide-field instruments are required. They must achieve high sensitivities and provide precise localizations in order to effectively study the objects. Wide field X-ray telescopes with imaging optics are expected to represent an important tool in future space astronomy projects in general, especially those for deep monitoring and surveys in X-rays over a wide energy range. The Lobster–Eye wide field X-ray optics has been suggested in 70ies by Schmidt (Schmidt, [10], orthogonal stacks of reflectors) and by Angel (Angel, [2], array of square cells). Up to 180 deg FOV may be achieved. This novel X-ray optics offers an excellent opportunity to achieve very wide fields of view (FOV, 1000 square degrees and more) while the widely used classical Wolter grazing incidence mirrors are limited to roughly 1 deg FOV(Priedhorsky et al., [9], Inneman et al., [7]).

LOBSTER EYE X–RAY TELESCOPES

Two basic types of Lobster Eye Wide Field X–ray telescopes have been proposed (Fig. 1). The telescopes in Schmidt arrangements are based on perpendicular arrays of double–sided X–ray reflecting flats. In the first prototypes developed and tested, double–sided reflecting flats produced by epoxy sandwich technology as well as gold coated glass foils have been used (Inneman et al., [8]). More recently, micro Schmidt lobster eye arrays with foils thickness as low as 30 microns have been developed and tested by our team in order to confirm the capability of these systems to achieve fine angular resolutions of order of a few arcmin (Figs. 3-4). The thin foils are separated by 70 microns gaps in these prototypes. On the other hand, large lobster eye systems with Schmidt geometry have been designed and constructed by us, achieving dimensions up to $300 \times 300 \times 600$ mm (Fig. 2). Their optical and X-ray optical tests (Fig. 5) 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 multi array 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 (Fraser et al., [4]).

For the alternative Angel Lobster lenses, numerous square cells of very small size (about 1×1 mm or less at lengths of order of tens of mm, i.e. with the length/size ratio of 30 and more) are to be produced. This demand can be also solved by modified innovative replication technology. Test modules with LE Angel cells have been successfully produced. The linear test module has 47 cells 2.5×2.5 mm, 120 mm long (i.e. length/size ratio of almost 50), surface microroughness 0.8 nm, $f = 1300$ mm. Another test module is represented by a L–shaped array of $2 \times 18 = 36$ cells of analogous dimension. The surface microroughness of the replicated reflecting surfaces is better than 1 nm.

Noteworthy 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 missions. 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.

From the technological point of view, the fact that 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 is important: all are based on either planparalel 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 dimensions (Gorenstein, [6]).

SCIENCE

Deep (limiting flux of 10^{-12}erg cm^{-2}s^{-1} can be easily achieved for daily scanning observation) X–ray sky monitoring with large FOVs (e.g. FOV of 6 $\times$ 180 deg can be easily assembled on the space station ISS or another spacecraft) is expected to contribute significantly to various fields of modern astrophysics. A few most important examples are listed below. They are given for Multi Foil Optics Lobster Eye Modules, designed as an alternative for an ISS like experiment (with easy modification for other space experiments), array of 30 modules, one module with 2 x 195 plates 78 x 11.5 x 0.1 mm, 0.3 mm spacing, detector pixel size 150 microns, total front area 1825 cm^2, energy range 0.1 - 10 keV, FOV 180 x 6 degrees (30 modules 6 x 6 degrees), angular resolution 3 - 4 arcmin, and total mass less than 200 kg.

(1) Gamma Ray Bursts (GRBs). Detection rates of nearly 20 GRBs/year can be obtained for the prompt X–ray emission of GRBs, taking into account the expected GRB rate 300/year. (2) X-ray flashes. Detection rates of nearly 8 X–ray flashes/year are expected, assuming XRF rate of 100/year. (3) X-ray binaries. Because of their high variability in X-rays they will be one of major targets in LE observations. LE will be able to observe their short-time outbursts by long-term extended monitoring. Almost all galactic XRB are expected to be within the detection limits. (4) Stars. Because of the low X-ray luminosity of

Figure 1. The schema of Lobster–eye optics, both in Angel as well as in Schmidt arrangement, with cross–like structure of an distant optical point source (bottom left) and corresponding ray–tracing model (bottom right).

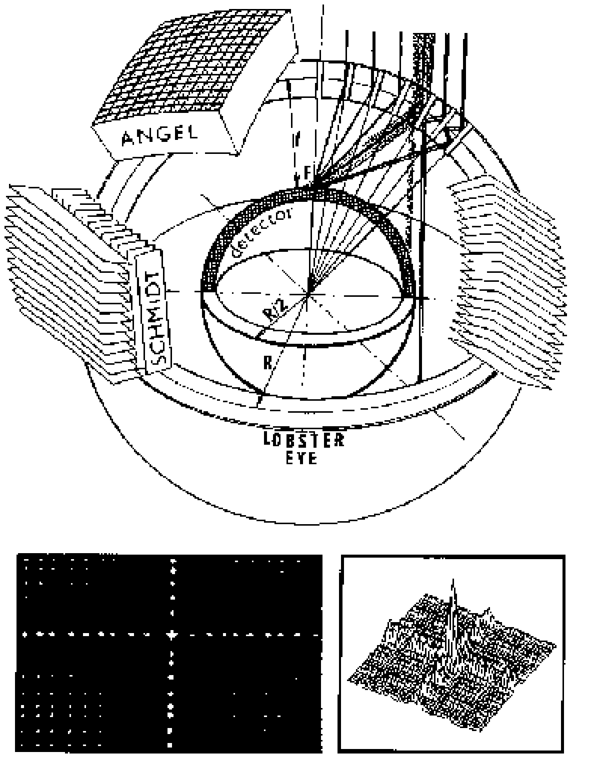


Figure 2. The large Lobster–eye optics module, with 300×300 mm gold-coated plates.

Figure 3. The micro Lobster–eye module, with 3×3 mm gold-coated plates, only 0.03 mm thick separated by 0.07 mm.

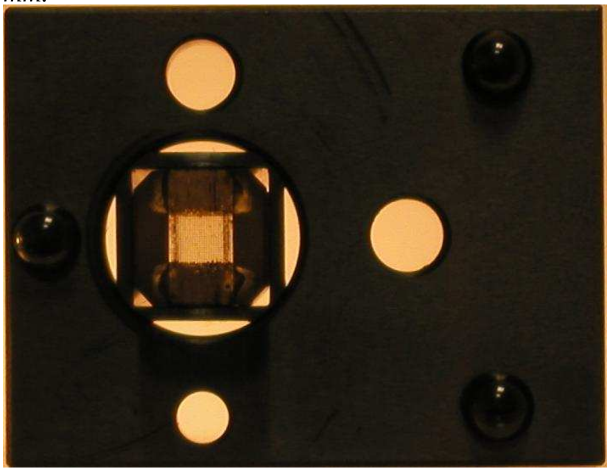


Figure 4. The front view of a mini Lobster–Eye Schmidt module, size 23×23 mm, based on thin gold–coated glass foils with thickness of 0.1 mm.

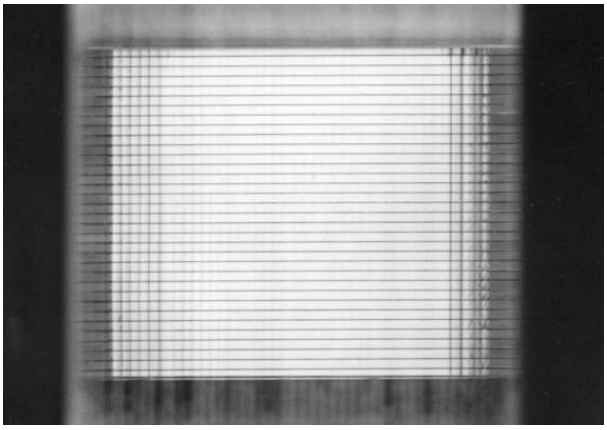


Figure 5. The focal image in the focal plane of the mini Lobster–eye optics module at 8 keV with a typical cross-like structure. The structure can be deconvoluted by mathematical programs.

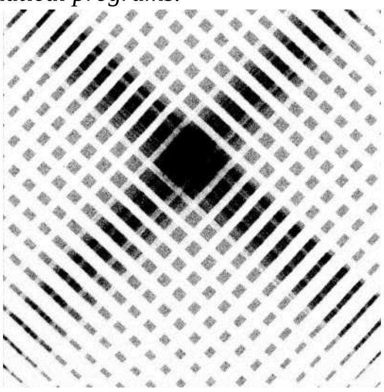


Figure 6. The numbers of known CVs observable by Lobster Eye ASM according to their individual types

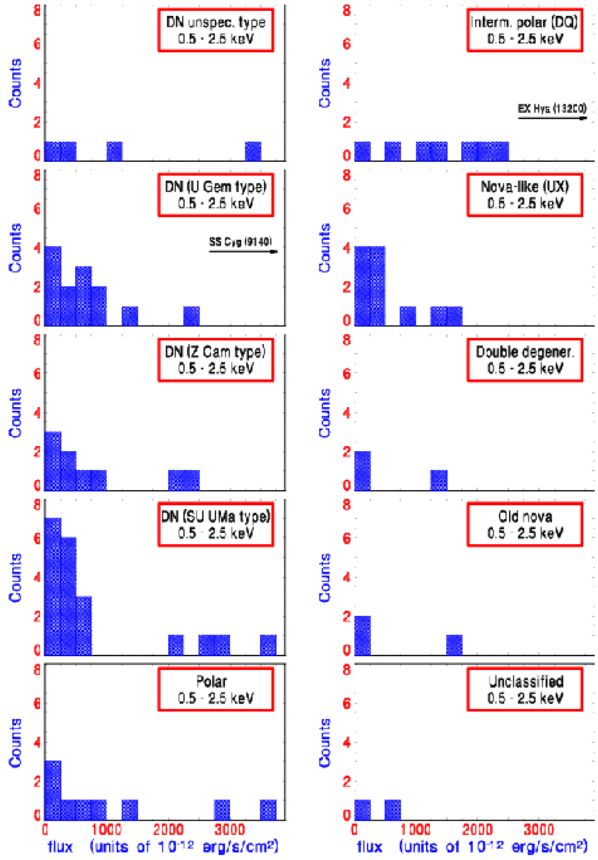


Figure 7. The numbers of all known CVs observable by Lobster Eye ASM

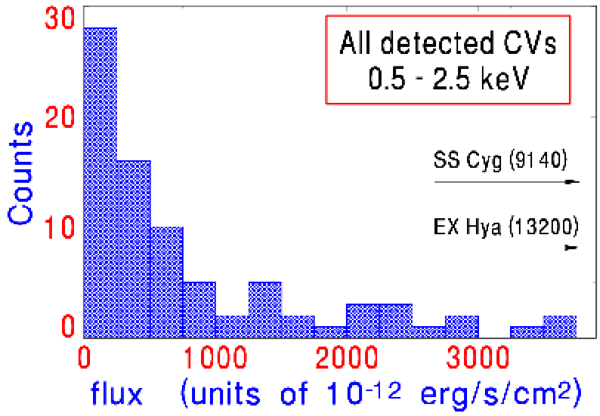
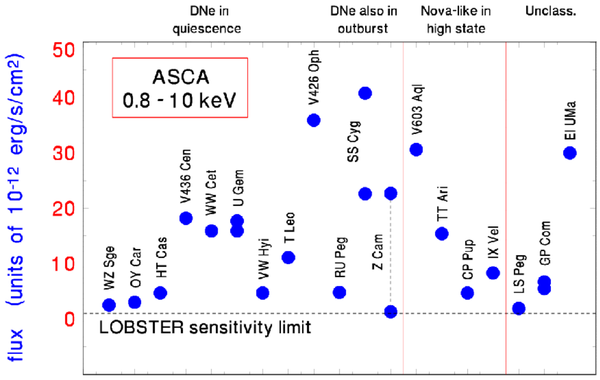


Figure 8. The various types of Dwarf Novae within the sensitivity limit of LOBSTER ASM



ordinary stars, only nearby stars are expected to be observable. We estimate the lower limit of ordinary stars observable by the LE telescope as 600. The sampling rate of LE observations will be sufficient enough to observe sudden X-ray flux increases during flares while still having the capability of monitoring the variability on time scales of years.(5) Supernovae. The LE telescope should be able to detect the theoretically predicted thermal flash lasting for $\sim$ 1000 sec for the first time. Together with the optical SNe detection rate and estimates of the LE FOV we estimate the total number of SNe thermal flashes observed by the LE experiment to $\sim$ 10/year. (6) AGNs. Active Galactic Nuclei will surely be one of the key targets of the LE experiment. LE will be able to monitor the behavior of the large ($\sim$ 1000) sample of AGNs providing long-term observational data with good time sampling (hours). (7) X–ray transients. The LE experiment will be ideal to observe X-ray transients of various nature due to its ability to observe the whole sky several times a day for a long time with a limiting flux of about 10^{-12}erg cm^{-2}s^{-1} . More and fainter X-ray transients are expected to be detected by the LE sky monitor enabling the detailed study of these phenomena. (8) Cataclysmic Variables. Cataclysmic Variables (CVs) are very active galactic objects, often showing violent long-term activity in both the optical and X-ray passband (outbursts, high/low state transitions, nova explosions) as well as rapid transitions between the states of activity. Search for the relation of the optical and X-ray activity is very important – monitoring of a large number of CVs is necessary to catch them in various states of activity. Most up to now X-ray observations of CVs: (i) Snapshots catching selected CVs in a particular state of activity, (ii) In most cases the transitions between the states are not covered, and (iii) Poor statistics of phenomena and objects (deeper studies available for only a few CVs). Important classes of CVs for LOBSTER are Non-magnetic dwarf novae (DNe), Supersoft X-ray sources (SSXSs), Classical novae (CNe), and Polars with soft X-ray excess (Figs. 6–8).

CONCLUSIONS

We conclude that the use of very wide field X–ray imaging system could be very valuable for many areas of X–ray and gamma–ray astrophysics. Analysis and simulations of Lobster–eye X–ray telescopes have been carried out. They have indicated that these innovative devices 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^{-2}s^{-1} for daily scanning observation as well as the angular resolution < 4 arcmin 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. The Lobster optics based All Sky Monitor is capable to detect around 20 GRBs and 8 XRFs yearly and this will surely significantly contribute to the related science. More details on the advantages of LE X-ray telescopes in scientific analysis of SNe are given in Sveda et al., [11]. 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 (3×3 mm) as well as large lenses (300×300 mm) have been developed, constructed, and tested. This makes the proposals for space projects with very wide field lobster eye optics possible for the first time.

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