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Lobster Eye Telescopes as X-ray All–Sky Monitors

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Abstract We report on the proposal of an All-Sky X-Ray Monitor based on wide-field X-ray telescopes with high sensitivity. 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.

Key words: X-ray telescopes – Lobster-Eye – X-ray optics

1 INTRODUCTION

The X-ray sky monitoring such as provided by RXTE and related scientific results (e.g. Wen et al. 2006) confirms the importance of X-ray All-Sky Monitors (ASM). Since the RXTE does not include optics, the much better results are expected if the survey sensitivity could be further improved (by implementing optical wide-field devices) by a factor of 10 – 100 or even more. As confirmed by RXTE and many other experiments (e.g. Wen et al. 2006), the X-ray sky 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. 2004; Frontera et al. 2004). For classical GRBs, the X-ray afterglows are detected in $\sim$ 90% of the cases (De Pasquale et al. 2003). 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, since the survey sensitivity could be further improved by a factor of 10 – 100 or even more. The Lobster-Eye wide field X-ray optics has been suggested in 70 s by Schmidt (Schmidt 1975, orthogonal stacks of reflectors) and by Angel (Angel 1979, array of square cells). 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. 1996; Inneman et al. 2000). In this paper, we introduce and discuss results obtained by our group, including experimental results i.e. assembled and tested laboratory samples of the Lobster-Eye modules. For more detailed instrumental issues (see e.g. Hudec et al. 2004; Sveda et al. 2004), while some novel approaches to wide-field X-ray optics are presented in Sveda et al. (2005b).

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Table 1 The single Lobster Eye Schmidt modules developed so far by our collaboration. Here plates have dimensions of $d \times l \times t$ and are arranged with spacing a. The modules have focal length f and field of view FOV and are optimized for the energy given in the last column.

Module	size d[mm]	thickness t[mm]	distance a[mm]	length l[mm]	foc. length f[mm]	resolution r[arcmin]	FOV [°]	energy [keV]
macro	300	0.75	10.80	300	6000	7	16	3
middle	80	0.3	2	80	400	20	12	2
mini 1	24	0.1	0.3	30	900	2	5	5
mini 2	24	0.1	0.3	30	250	6	5	5
micro	3	0.03	0.07	14	80	4	3	10

2 THE INSTRUMENTAL SOLUTION FOR THE X-RAY ASM

The idea of sensitive X-ray ASM is based on the use of wide-field X-ray optics which, in general, improves the signal to noise ratio. The suitable technical solution is offered by wide-field optics of Lobster Eye type. In the past, two basic types of Lobster Eye Wide Field X-ray telescopes have been proposed. 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. 1999, see also Table 1). The laboratory samples listed in this table and discussed below have been developed by our collaboration. More recently, we have developed and tested micro Schmidt lobster eye arrays with foils thickness as low as 30 microns 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 70 microns gaps in these prototypes. On the other hand, we have designed and constructed large lobster eye systems with Schmidt geometry, achieving dimensions up to $300 \times 300 \times 600$ mm. Their optical tests have confirmed the expected performance according to calculations (computer ray-tracing). Our 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 RSG mission Lobster experiment, presently under study (including the angular resolution and with better transmission) and can hence represent an alternative to the recently suggested MCP technique (Fraser et al. 2002).

Another alternative is represented by Angel Lobster lenses, based on 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). This demand can be also solved by modified innovative replication technology. Test modules with LE Angel cells have been successfully produced by our group. 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.

For the X-ray ASM, a modular concept with arrays of individual Lobster modules seems to be advantageous as in this case planar X-ray detectors could be used. Such way, a larger FOV can be easily achieved, depending on the number of modules. 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 (e.g. Gorenstein et al. 1998) 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.

3 SCIENTIFIC ASPECTS

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 6×180 deg can be easily assembled on the space station ISS or on alternative spacecraft) is expected to contribute significantly to various fields of modern astrophysics. The results of simulations of the sky coverage and of the limiting flux are illustrated in Figures 1 and 2. The gain, computed from a ray-tracing simulation, is shown in Figure 4, and the simulated on-axis effective

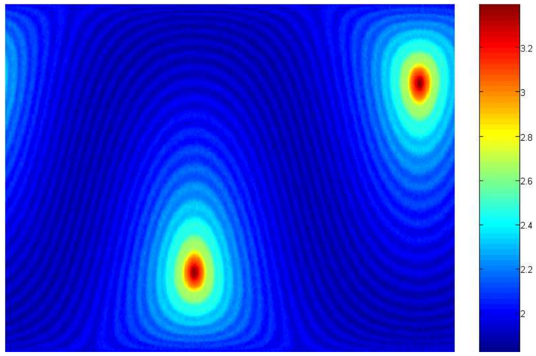

Fig. 1 The simulation of the sky time coverage by the ASM based on 30 LE modules, one module has 2×195 plates $78 \times 11.5 \times 0.1$ mm, 0.3 mm spacing, detector pixel size 150 microns, total front area 1825 cm^2, energy range 0.1 – 10 keV, FOV 180 x 6 degrees (for 30 modules 6×6 degrees each), angular resolution 3–4 arcmin, total mass $<$ 200 kg for 30 modules. The figure displays the log t, where t is the time equal to the on–axis observation by the LE module during the revolution of 90 min.

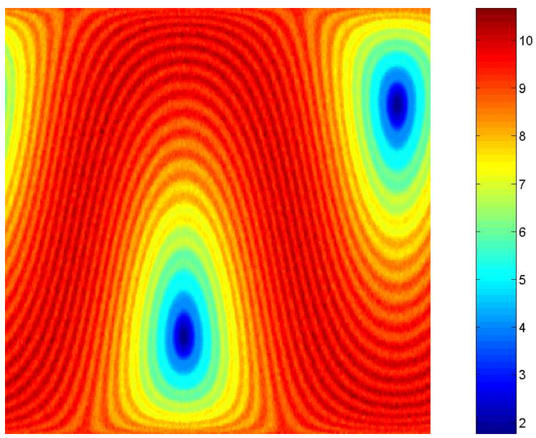

Fig. 2 The simulation of the limiting flux of an array of 30 LE modules, one module has 2×195 plates $78 \times 11.5 \times 0.1$ mm, 0.3 mm spacing, detector pixel size 150 microns, total front area 1825 cm^2, energy range 0.1–10 keV, FOV 180×6 degrees (for 30 modules 6×6 degrees), angular resolution 3–4 arcmin, total mass <200 kg for 30 modules. The figure displays the estimate of the limiting flux, in units of 10^{-12} erg cm^{-2} s^{-1}, of the instrument after one day (90 min. orbits) in the 0.5–2.5 keV energy range (Crab–like spectrum assumed).

area of one LE module in Figure 4. A few most important examples of scientific aspects of LE based X-ray ASM are listed below.

(1) Gamma Ray Bursts (GRBs). Detection rates of nearly 20 GRBs year^{-1} can be obtained for the prompt X-ray emission of GRBs, taking into account the expected GRB rate 300 year^{-1}. (2) X-ray flashes. Detection rates of nearly 8 X-ray flashes year^{-1} are expected, assuming XRF rate of 100 year^{-1}. (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 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 vari-

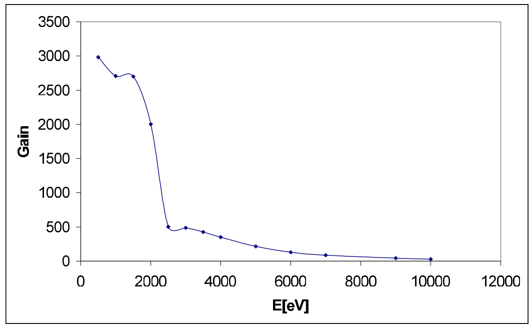

Fig. 3 The gain, computed from a ray-tracing simulation, as a function of the energy (for one module desribed in the Figs. above). We define gain as g=N1/N2 where N1 is the number of photons focussed by the LE into area of the size of FWHM (Full Width of Half Maximum) of the PSF (Point Spread Function) and N2 is the number of photons which would be detected in the same area without the focussing power of the LE (Sveda 2003).

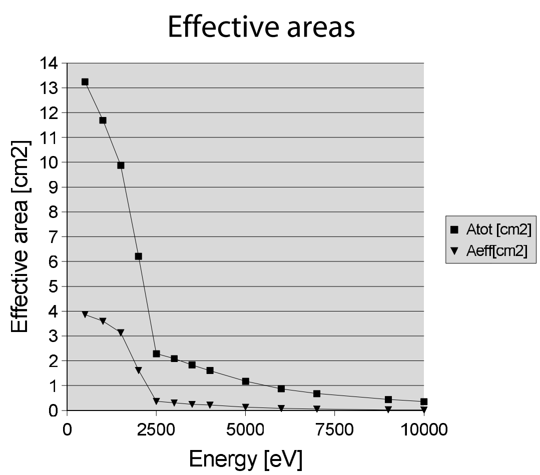

Fig. 4 The simulated on-axis effective area of one module as a function of the energy. The front area of the module is 78×78 mm. The effective area was computed from the ray tracing as Aeff=Afront(Wfoc/Wi) and Atot=Afront(Wr/Wi) where Afront is the front area of the LE system, Wfoc is the total weight of photons detected within the focal spot, Wr is the total weight of photons detected in the screen with at least one reflection and Wi is the total weight of all photons at the time of emission (Sveda 2003).

ability on time scales of years. (5) Supernovae. The LE telescope should be able to detect the theoretically predicted thermal flash lasting for ~ 1000 s 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 be ~ 10 year^{-1}. (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 (~ 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 include: (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.

4 CONCLUSIONS

Our analysis and simulations of Lobster-eye based X-ray ASM 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.

Our calculations show that the Lobster optics based ASM 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. (2005), the detection rates of LE ASM for GRBs and XRFs were also discussed by Amati et al. (2006). The various prototypes of both Schmidt as well as Angel arrangements have been produced and tested by our collaboration 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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References

Amati L. et al., 2004, A&A, 426, 415
Amati L. et al., 2006, Adv. Space Res. 38, 1333
Angel J. R. P., 1979, Astroph. J., 364, 233
De Pasquale M. et al., 2003, ApJ, 592, 1018
Fraser G. W. et al., 2002, Proc. SPIE, 4497, 115
Frontera F. et al., 2004, ApJ 616, 1078
Gorenstein P., 1998, Proc. SPIE, 3444, 382
Hudec R., Sveda L., Inneman A., Pina L., 2004, Proceedings of the SPIE, 5488, p.449
Inneman A. et al., 2000, Proc. SPIE, 4138, 94
Inneman A. et al., 1999, Proc. SPIE, 3766, 72
Priedhorsky W. C. et al.,1996, MNRAS 279, 733
Schmidt W. K. H., 1975, NucIM, 127, 285
Sveda L., 2003, Astrophysical aspects of Lobster Eye X-ray telescopes, Thesis, Faculty of Mathematics and Physics, Charles University, Prague
Sveda L., Hudec R., Pina L., Inneman A., 2004, in X-Ray Sources and Optics. Edited by MacDonald, Carolyn A., Macrander, Albert T., Ishikawa, Tetsuya, Morawe, Christian, Wood, James L., Proceedings of the SPIE, 5539, p.116
Sveda L. et al., 2005, in Cosmic Explosions, Springer Proceedings in Physics, Vol. 99, Eds. J. M. Marcaide, K. W. Weiler, p.197
Sveda L., Semencova V., Inneman A., Pina L., Hudec R., 2005b, in Fourth Generation X-Ray Sources and Optics III. Edited by Tatchyn, Roman O., Biedron, Sandra G., Eberhardt, Wolfgang, Proceedings of the SPIE, 5918, p.22
Wen L. et al., 2006, ApJ, 163, 372