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Biomimetics and astronomical X-ray optics

R. Hudec[1,3] **and K. Remisova**[2]

[1] *Czech Technical University in Prague, Faculty of Electrical Engineering Technicka 2, Prague 166 27, Czech Republic (E-mail: hudecren@fel.cvut.cz)*

[2] *Charles University, Faculty of Science, Prague, Czech Republic*

[3] *Kazan Federal University, Russian Federation*

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Abstract. Some sea and water animals have strange mirror eyes which have (or might have) potential application in science and technology in general and in X–ray astrophysics in particular. While the principles of mirror eyes of decapods (lobsters, crayfishes) are already applied in space and ground–based imaging experiments, the mirror eyes of specific fishes are still very little investigated.

Key words: Lobster eye optics – X-ray monitoring– Biomimetics

1. Introduction

The principles of biomimetics were succesfully applied in space X–ray optics in the past and recently, e.g. in Lobster-Eye optical wide–field imaging systems. In addition, the recent growing knowledge of sea vision, especially of peculiar mirror eyes of scallops, crustaceans, and deep sea fishes, makes possible to consider other such applications. Perhaps the most important new discovery is deep sea fish *Rhynchohyalus natalensis* with mirror eyes based on very large numbers of very small mirrors developed from the choroidal argentea with crystals orienteted almost parallel to the mirrors surface. This arrangement may even include principles of active optics.

We report briefly on ongoing study with focus on understanding of very specific mirror eyes of sea animals and how they may help us to design and develop special optics for scientific applications. We study the ways these mirror eyes work, what are the advantages of these peculiar eye arrangements, and whether these optics can be used in advanced devices, e. g. space and especially X–ray optics. Here we very briefly present and discuss the preliminary results.

In general, photons (fundamental particles of light) heading into an eye are focused on retina and detected by photoreceptors located there. Consequently, the information about the presence of light is converted into neuronal impulses, which are then led into a brain. In the brain, the information is further processed and the signals are converted to images. Finally, these images are recognised and interpreted through cognitive processing (Remisova, 2016) and (Hudec & Remisova, 2016) and references therein.

Each part of the visual pathway from the light detection through the information processing to the image interpretation may be modified in many ways. In this bachelor thesis, I mostly focus on the morphological modifications of the optical systems, particularly on the so-called mirror eyes. The mirror eye type is an image-forming arrangement based on reflection of a biological mirror, which is very unique since the majority of the eye systems utilise refraction of lenses (Remisova, 2016) and (Hudec & Remisova, 2016) and references therein.

Biological mirrors are special type of tissue usually made of many layers of material with alternating high and low refractive indices. Light reflects from the upper and lower surfaces of each layer; the reflections interfere and create images (Land, 1972).

The mirror eye arrangement can be found mostly in animals living in the dim or deep water, such as scallops, shrimps, prawns or even some fishes. The first documented mirror eyes were optical systems of scallops, demonstrated by Land in 1965 (Land, 1965), and of shrimps, described by Vogt in 1975 (Vogt, 1975). The latest discoveries show that mirror eyes can be found even in vertebrates, such as fishes *Dolichopteryx longipes* and *Rhynchohyalus natalensis* (Remisova, 2016) and (Hudec & Remisova, 2016) and references therein.

The mirror optics used in these special eyes is also applicable in technical area. Already in past century, Angel (Angel, 1979) came up with an idea of technical application of the mirror eye arrangement. He proposed to imitate principle of decapod eye imaging to construct a high-energy responsive telescope with wide field of view. Eventually, this so-called lobster-eye X-ray telescope was assembled and it is nowadays used in astronomical satellites, such as VZLUSAT-1 (Pina et al., 2014, 2015; Pína et al., 2016).

2. Animal mirror eyes

For some time, it was not known how the decapod crustaceans see since the optical features of their eyes did not correspond with the refractive formation of images. In 1975, Vogt (Vogt, 1975) described the crayfish eye as a reflective superposition eye. Right after that, Land (1976) described another decapod shrimp having the same type of eye. Later on, it has turned out that several crustacean species, e.g. the *copepod Sapphirina* or the *ostracod Notodromas*, possess even other types of mirror eyes.

Decapods. Though decapods possess superposition eyes, they differ from those of insects. While in insects facets are shaped as hexagons, decapods have square facets. Moreover, the refractive indices are usually high and possessing a gradient in insects, but they are quite low and roughly homogeneous in decapods. Vogt (1975) (Vogt, 1975) found out that the crayfish eye use reflective optics rather than refraction since the crystallin cones and multi-layered tissue, which encloses them, both together form orthogonal reflectors. Such arrangement can be found also in other long-bodied decapod crustaceans, e.g. prawns and lobsters, however, not in hermit and true crabs. We refer to (Remisova, 2016) and (Hudec & Remisova, 2016) for the full list of references.

The compound eye of the crayfish Astacus consists of thousands of ommatidia. Each ommatidium compounds of a corneal facet, a crystallin cone (divided into two parts distal and proximal) surrounded by pigment cells, a rhabdom consisting of 8 retinular cells, a tapetum and a basement membrane. The corneal facet has a squared shape and homogenous refractive index. It works as a weak lens to pre-focus light.

The eyes of other crayfish species may significantly vary from the eyes of *Astacus*. For example, the reflecting superposition eyes of the crayfish *Cherax destructor* possess corneal facet lenses for better light focus. The shrimp *Oplophorus spinosus* has almost spherical superposition eyes. The cones material is of too low refractive index to be able to form an image by refraction. However, the cone sides are internally covered by a layer of reflecting material; therefore, they work as biological mirrors. The incoming light reflects at one of the sides of each cone. Finally, the image is formed due to the thin-film interference.

Relatively recent is the knowledge of fish mirror eyes. In 2009, *Dolichopteryx longipes* was described by Wagner et al. (Wagner et al., 2014) as the first vertebrate possessing mirror eyes. In 2014, Partridge et al. (Partidge, 2014) described another fish, *Rhynchohyalus natalensis*, with reflective optics that belongs to the same family of fish *Opisthoproctidae* (also known as barreleyes or spook fishes) as *Dolichopteryx longipes*. Although the mirror eyes (diverticula) of these two species are similar, they vary in two important attributes the origin of the reflective tissue and the orientation of their reflective plates. We refer to (Remisova, 2016) and (Hudec & Remisova, 2016) for the full list of relevant references.

3. Biomimetics of animal mirror eyes

The biomimetics is an interdisciplinary field whose innovations are used in many other fields, such as engineering, electronics, nanotechnology, robotics, artificial intelligence, biosynthesis, bioengineering etc. There have been various successful achievements of biomimetics, like for example self-cleaning surfaces, antireflective surfaces, camouflage principles, designs of ships and aircrafts, building designs, microstructures and nanomaterials, biomaterials, artificial textiles, artificial tissues and organs, implants, self-healing materials, biosensors and many more.

The reflective superposition eyes of decapods described earlier served as an inspiration for innovation in the field of astrophysics the lobster-eye X-ray telescopes. While the decapod eyes work in the visible spectrum, the technical applications of the lobster-eye telescope work in the field of X-ray imaging at energies from 0.1 to 10 keV. For the X-ray application, the cones have to be much longer than in the decapod eyes. Such mirror channels distributed over a spherical surface reflect rays at very small angles of incidence called grazing angles and bring them to focus (Angel, 1979). The image of a point source gained from this kind of device shows a single peak (created by rays reflected from both the horizontal and the vertical walls) accompanied with a cruciform structure (created by rays reflected either from the horizontal or from the vertical walls) and a background. An advantage of such arrangement compared to a concave spherical mirror is that the field of view may be made as large as needed by covering more of the sphere with the square channels. Therefore, the lobster-eye X-ray telescopes may be used as all-sky monitors. Another advantage is that it works at wide range of grazing angles, and thus it is effective even at low energies with a large collection area in comparison to other X-ray optics. Recently, numerous lobster-eye X-ray arrangements have also been designed, developed and tested in the Czech Republic. For instance, this lobster-eye optics is used in the first Czech technological nanosatellite VZLUSAT-1 that will be launched in 2017 (Pina et al., 2014, 2015; Pína et al., 2016).

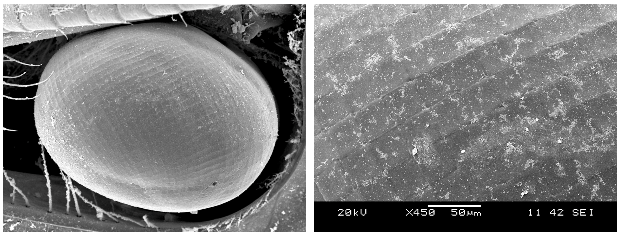

Figure 1. The eye of small (1 cm length) crayfish Orconectes limosus under electron microscope.

4. Lobster telescopes as example of biomimetical application

The LOBSTER X–ray telescopes are based on the optical arrangement of the lobster eye. The main difference from classical X-ray space telescopes in wide use is the very large field of view while the use of optics results in higher efficiency if compared with detectors without optics.

The LobsterEye (LE) telescopes are based on grazing incidence optics analogous to those in eyes of lobsters, shrimps, and crayfish (Fig. 2). Two basic types of Lobster Eye Wide Field Xray telescopes have been proposed for astrophysical applications (Angel, 1979), (Schmidt, 1975) (Fig. 5). The telescopes in Schmidt arrangements are based on perpendicular arrays of doublesided Xray reflecting flats (Fig. 5).

Recent innovative technologies have enabled to design, to develop and to test first prototypes (Fig. 8). They will provide deep sensitive survey of the sky

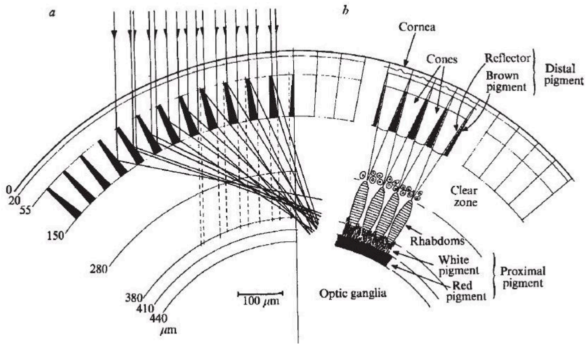

Figure 2. The principle of reflective animal eye. Optical (a) and Anatomical (b) Structure of Part of the Eye of the Shrimp Oplophorus. In (a) i tis assumed that the only optical components in the eye are the reflector-lined faces of the cones. Solid lines show how reflected light is brought to a focus; dashed lines indicate pencils of rays that pass through directly. The numerals on the left show the depth of each layer from the surface. (b) shows the parts of the eye as visible in a hemisected eye seen through a dissecting microscope (figure and legend modified after Land, 1976). Lobster and crayfish have analogous eye arrangements.

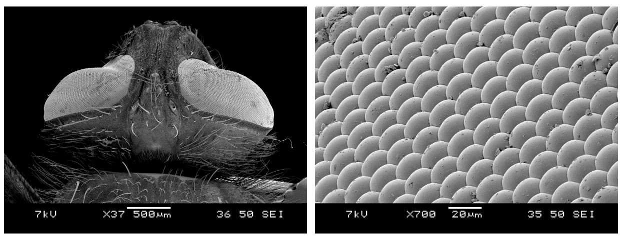

Figure 3. The eye of fly under electron microscope (for comparison)

in X-rays for the first time which is essential for both long-term monitoring of celestial high-energy sources as well as in understanding transient phenomena. The technology is now ready for applications in space (Hudec et al., 2015; Urban et al., 2016; Baca et al., 2016; Dániel et al., 2016).

4.1. Lobster eye optics

The Lobster eye optics works on reflection principle as well as the commonly used Wolter I X–ray optics. There are two arrangements of LE optics, Angel's and Schmidt's (Angel, 1979), (Schmidt, 1975).

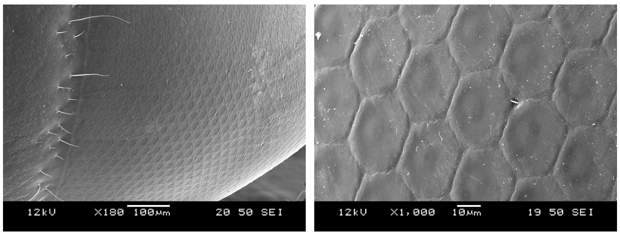

Figure 4. The eye of water boatman under electron microscope (for comparison)

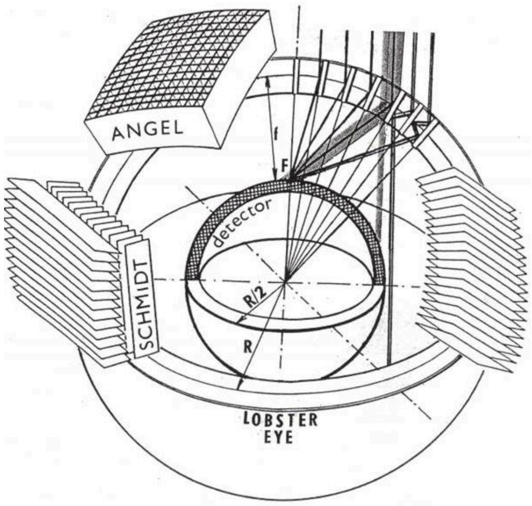

Figure 5. The principle of LE X–ray optics. There are 2 basic LE X–ray optics arrangements, namely Angel and Schmidt, both are illustrated by this figure, first described by (Angel, 1979) and (Schmidt, 1975).

One dimensional lobster-eye geometry was originally suggested by Schmidt (Schmidt, 1975), based upon flat reflectors arranged in an uniform radial pattern around the perimeter of a cylinder of radius R. X-rays from a given direction are focussed to a line on the surface of a cylinder of radius R/2 (Fig. 5). 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. Focussing 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

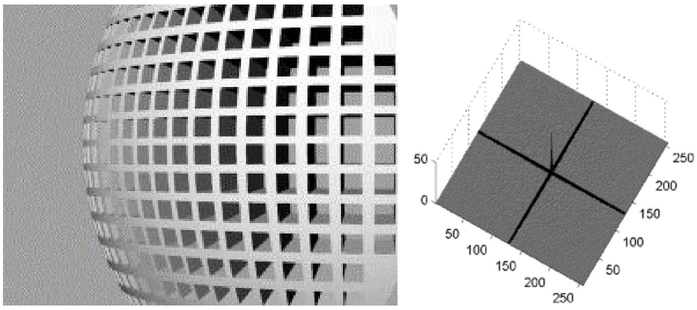

Figure 6. The Angel LE optics principle (left) and The PSF example for the mentioned optics, pixel size scaled to 2 px/FWHM (right)

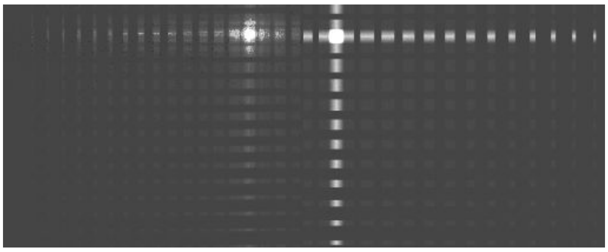

Figure 7. The experiment (left) and the simulation (right) of the 8 keV point-to-point focusing system. The gain defined as a ratio of the maximum value of the pixel and the value of the directly illuminated pixels is 570 for the experiment and 600 for the simulation. The FWHM of both peaks is also close to each other. The focal length of the system is f = 1.2 m, the pixel size is 24 microns

half sphere 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 offer a field of view of up to 1000 square degrees at a moderate angular resolution.

It is obvious that this type of X-ray wide field telescopes will 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 early proposals was the All Sky Supernova and Transient Explorer (ASTRE). More recently, the Lobster Eye Optics in Microchannel Plate (MCP) design was considered for the LOBSTER ISS space experiment. There is also potential for possible extending the wide field

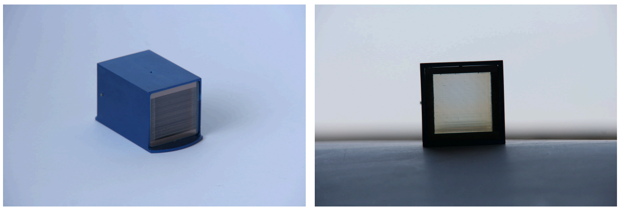

Figure 8. Mini LE 2D module front aperture 23 x 23 mm and f 250 mm. Such miniature module is suitable for application on picosatellites.

imaging system to higher energy by the use of multilayer or other coatings in analogy to those described for flat reflectors in the Kirkpatrick-Baez geometry.

There is also an alternative based on slightly different arrangement, sometimes referred as two-dimensional lobster eye optics (Angel, 1979). The idea of two dimensional lobster-eye type wide-field X-ray optics was first mentioned by Angel. 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 (Figs. 5 and 6). 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.

5. Conclusion

The mirror eye is an eye type unique for using reflection of biological mirrors rather than refraction of lenses or corneas for image forming. This eye type is quite rare in the animal kingdom and it can be found only in several species of molluscs, crustaceans and fishes living in the dim or deep water. This paper represents the review about the mirror eyes including comparison of invertebrate and vertebrate mirror eyes, which has never been compared before. The current knowledge about most of the mirror eye types remains largely incomplete and future research is necessary to fully understand this rare and fascinating structure employed in vision. Though several types of mirror eyes have been described, the majority of them were reported by examination of a single specimen due to the logistical difficulties in obtaining deep sea samples. The physical (optical) parameters were rarely measured in live organisms; most of them come from the ray tracing of the eye models instead. However, there are very few such results so far. Therefore, the information about the mirror eyes is very limited and in many cases even unavailable. For better understanding, more detailed anatomical examination is needed (e.g. of the ultrastructure of multilayer reflectors) as well as molecular and genetic analyses together with advanced mathematical modelling of the ocular performance and investigating the image created in live specimens. In future, there is an enormous potential of further studies, especially of biomimetic application of some principles of the mirror eyes, such as the light and dark adaptation in the superposition eyes of crustaceans or the tilting of mirror plates in the recently described eyes of the spookfish (Dolichopteryx longipes). The principles of animal (lobster) eye were successfully applied in X–ray astronomy experiments (wide–field imaging and sky monitoring) with further potential applications.

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