ESA's Response to the Challenges of Developing X-ray Optics

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ESA is currently developing the X-ray optics for its future astrophysics and planetary missions, following on from the highly successful XMM-Newton mission. The next generation of astrophysics missions such as XEUS will require dramatic improvements in the performance, size and mass of the telescope, which is the heart of any high-energy astrophysics mission. This article highlights the challenges and identifies some possible technology solutions.

Introduction

Europe has a strong heritage in X-ray optics, with X-ray astrophysics missions such as Exosat (ESA), Rosat (D), Beppo-SAX (I) and XMM-Newton (ESA), but a further major evolution of the technology is required to satisfy growing future demands. The main technological drivers remain a dramatic increase in effective area, coupled with good angular resolution of order 1–10 arcsec. These two parameters are coupled, but must be improved while ensuring a reduction in mass as well as an overall reduction in X-ray mirror fabrication costs.

Since there is no material that efficiently refracts X-rays, reflection optics are used for astrophysics and possible future planetary space missions. The reflection occurs efficiently over a large range of photon energies only if the X-rays are reflected with a small grazing angle - typically below 1 deg. The geometry of choice is known as a Wolter-I configuration for X-ray energies from 0.1 to 10 keV, i.e. photon wavelengths of 10 – 0.1 nm. This configuration comprises, as a basic element, a paraboloid (P) coupled to a hyperboloid (H), as shown in Figure 1. To achieve a reasonably large collecting area, pairs of shells (P+H) are stacked inside each other, like Russian dolls, and the mirror system is said to be 'nested'. To ensure an adequate imaging resolution, these shells must be stiff and well-aligned, leading to bulky and heavy optics. Table 1 summarises the major characteristics of the Wolter-I mirrors flown to date.

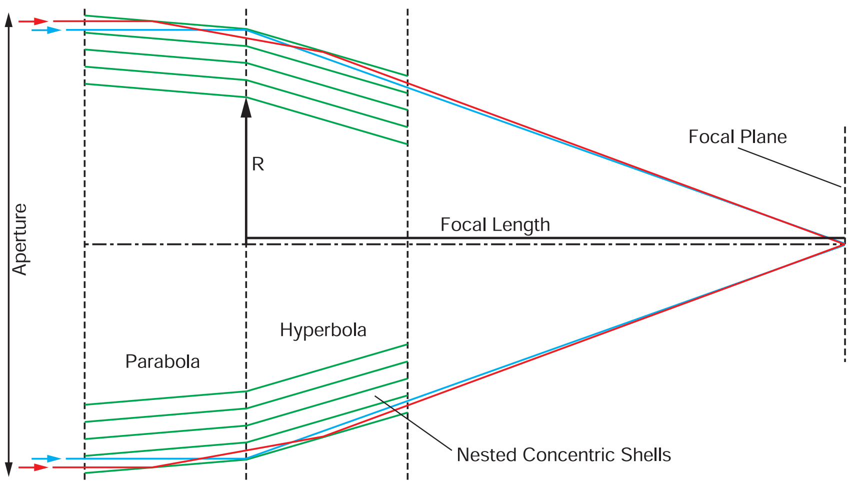

Figure 1. Schematic of a Wolter-I X-ray telescope showing the key characteristics

In Table 1, FOV refers to the field of view of the X-ray mirror system, while R is the imaging resolution on- axis. The effective area is also provided at a nominal energy of 1 keV (1 nm). All data refer to a single mirror module. In the case of some mirror systems, more than one module was flown to achieve an increase in collecting area. This duplication of mirror modules, however, requires the same duplication of focal-plane instruments.

A few issues are immediately evident from Table 1. Firstly, since the first imaging telescope for cosmic X-ray astronomy was flown (the Einstein Observatory) in 1978, the capabilities of the telescopes have evolved enormously, particularly with respect to focal length, which governs the upper energy (short wavelength) cut-off threshold of the mirror, and collecting area. The two current major observatories in orbit, NASA's Chandra and ESA's XMM-Newton, drive technology in two different directions. For Chandra the emphasis is on imaging resolution at the expense of collecting area, while for XMM-Newton the imaging capability has been relaxed while the collecting area has been increased. In fact, the collecting area in the case of XMM-Newton was achieved through the dramatic increase in the nesting of the shells together with the fabrication of three

*Table 1. A summary of the principal characteristics of Wolter-I X-ray mirror systems flown to date**

Mission	Agency	Launch (yr)	Lifetime (yr)	Mass (kg)	Nest	Focal Length (m)	Number Modules	Aperture (cm)	FOV (arcmin)	R (arcsec)	Area (cm^2) (@ 1 keV)
Einstein	NASA	1978	2.5	~ 460	4	3.5	1	56	75	~ 2	1x200
Exosat	ESA	1983	3	7	2	1	2	30	120	~ 18	2x35
Rosat	DLR	1990	9	950	4	2.4	1	84	120	1.7	1x400
BeppoSax**	ASI/NIVR	1996	6	13	30	1.85	4	16	30	60	4x80
Chandra	NASA	1999	~5–10	956	4	10	1	120	30	0.5	1x750
Newton	ESA	1999	~5–10	350	58	7.5	3	70	30	12	3x1500
XEUS	ESA	>2012	~25	?	?	50	1	1000	5	2–5	1x300 000

* No-foil optics, which also use a conical approximation to Wolter-I optics, are included here because they provide resolutions above 1arcmin.

** Conical approximation to Wolter-I optics.

identical modules. Figure 2 shows one such XMM-Newton module prior to integration into the spacecraft. Each mirror module manufactured from electro-formed nickel shells has a mass of 350 kg. The masses of the Chandra and XMM-Newton mirrors are essentially the same, with the ratios of the key parameters for the two missions, namely collecting area and resolution, being about 6 and 20, respectively. Figure 3 illustrates the importance of resolution to separate faint discrete X-ray sources versus collecting area. A large collecting area allows sufficient X-ray photons to be detected to allow the spectra of X-ray sources to be determined, while good spatial resolution ensures that overlapping sources are not confused.

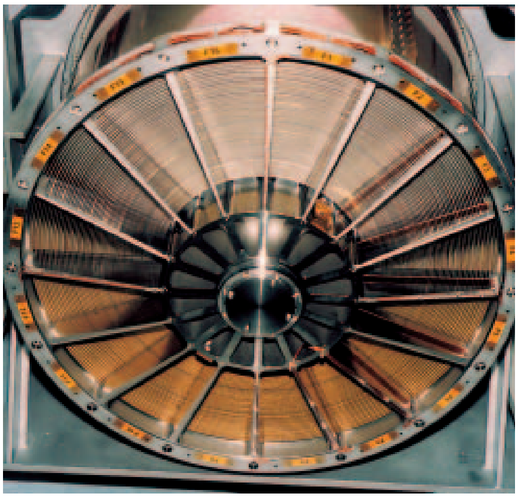

Figure 2. A single XMM-Newton flight-model mirror prior to integration into the spacecraft. The 58 mirror shells with diameters ranging from 30 to 70 cm, each manufactured from electro-formed nickel with a typical thickness of 1 mm from a high-quality mandrel, are stacked like Russian dolls inside each other with an inter-shell spacing of typically a few mm. These shells have to be aligned and fixed rigidly with respect to each other and the nominal X-ray focus, to achieve the high overall system resolution of 12-15 arcsec

For predicting the main evolutionary factors required of X-ray mirror systems over the next few years, we use the requirements for XEUS, an ESA mission under study as the potential successor to XMM-Newton in partnership with Japan. Here, the requirements have increased enormously, the mirror having a diameter of 10 m and a focal length of 50 m, but the collecting area and resolution are now 30 m^2 and 2 arcsec, respectively. To build such a huge mirror system and still achieve such a high image quality is a real challenge. A figure of merit that demonstrates both the optic and programmatic challenge is the collecting area to mirror mass ratio, which is shown in Figure 4 for the missions listed in Table 1.

Alternative technologies

ESA, together with European industry and research institutes, is exploring the X-ray optics technologies for the next generation of space astrophysics and planetary missions currently being designed. A number of technologies are

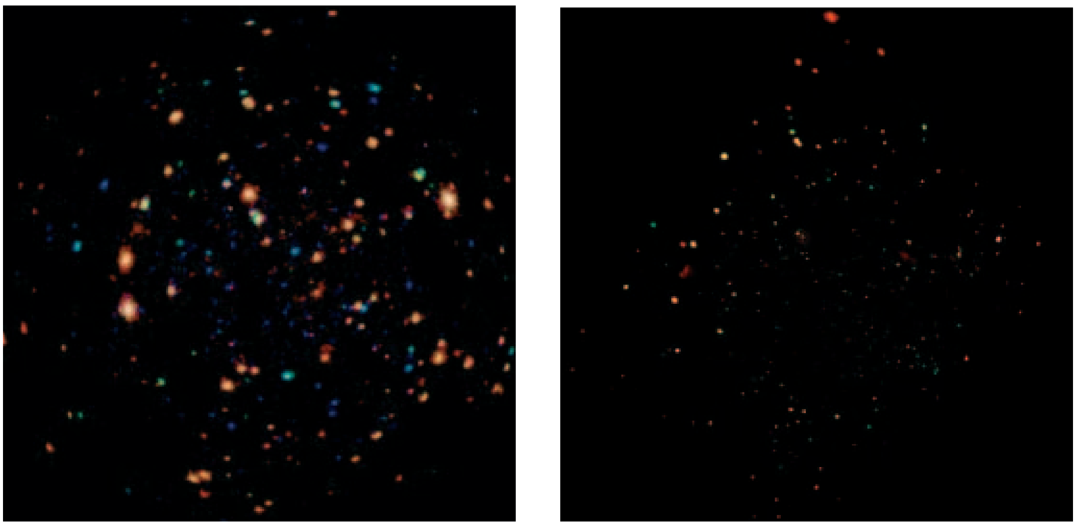

Figure 3. Images of a deep field – a region of blank space – observed with XMM-Newton (left) and Chandra (right). XMM-Newton detects many more photons so as to measure the source spectra, while Chandra ensures that overlapping sources are clearly separated. Both complement each other in resolving and understanding the discrete sources that form the X-ray background. This background is of major cosmological importance. Future generations of X-ray mirrors will need to do the same as these two missions, but with a single mirror system having even more (~ 200 times) collecting area to probe even deeper into the Universe and thereby look back in time to when it was very young

under study, ranging from low-mass replication processes built around conventional Wolter-I nested geometries to radically different approaches. In the latter case, the technology used to produce glass micro-channel plate (MCP) image intensifiers is used to produce X-ray optics with very thin reflecting surfaces, of the order of only a few microns. This results in an MCP optic that is far lighter and smaller than would be possible with conventional grazing-incidence optics. As shown in Figure 5, a conical approximation to the Wolter-I geometry is employed, and a radial arrangement of the MCPs is required. In a sense, the nested shell set of Russian dolls has been replaced by a massive set of micro-shells, all configured to focus X-rays at the same spot.

For the first time such a compact and light lens has been made with a geometry that produces true X-ray imaging. This lens has been manufactured under ESA contract by Photonis (F) with support from Leicester University Space Centre (UK). Testing has been performed by ESA staff and COSINE Research BV (NL) in collaboration with the Bessy PTB synchrotron facility in Berlin (D) and the European Synchrotron Radiation Facility (ESRF).

Microchannel plates have been developed for image intensifiers and photon-counting detectors, and their mass production has reached a high level of optimisation. Due to the production process, which involves severe stretching of the glass fibres, very smooth walls are obtained, which are arranged in a regular geometry. Starting with a slab of material, the glass is drawn into long thin fibres, which are then grouped into multi-fibres and drawn again. Finally, these multi-fibres are stacked with the desired geometry and then fused to form a monolithic block. The block is then cut into slices, which are etched to form pores. Finally, the resulting plates are slumped into the required shape.

To adapt the MCPs for use as X-ray optics, it was necessary to change and improve the multi-fibre geometry and reduce the surface roughness, which scatters X-rays and thereby degrades the image quality. The later has been achieved by polishing the starting blocks of glass used to produce the fibres. The geometry was a greater challenge because traditional MCPs are based on round fibres. For imaging applications, square fibres are required, which in turn require modifications to the drawing towers and the introduction of appropriate on-line metrology. The resulting optics are, however, very rigid, extremely light and very robust, since the specific mass and the corresponding forces during vibration are low.

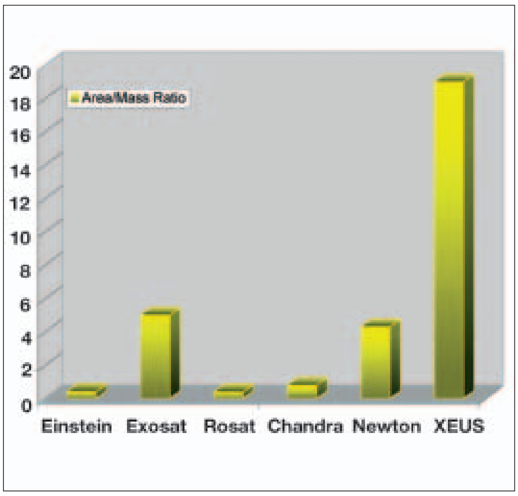

Figure 4. The mirror area-to-mass ratio, a figure of merit that illustrates the improvement in performance of X-ray mirrors over the last twenty years or so and the huge strides still needed to satisfy the requirements of future X-ray mirror missions such as XEUS. Care must, however, must be exercised when making comparisons between the various missions because imaging resolution is another merit parameter that needs to be considered

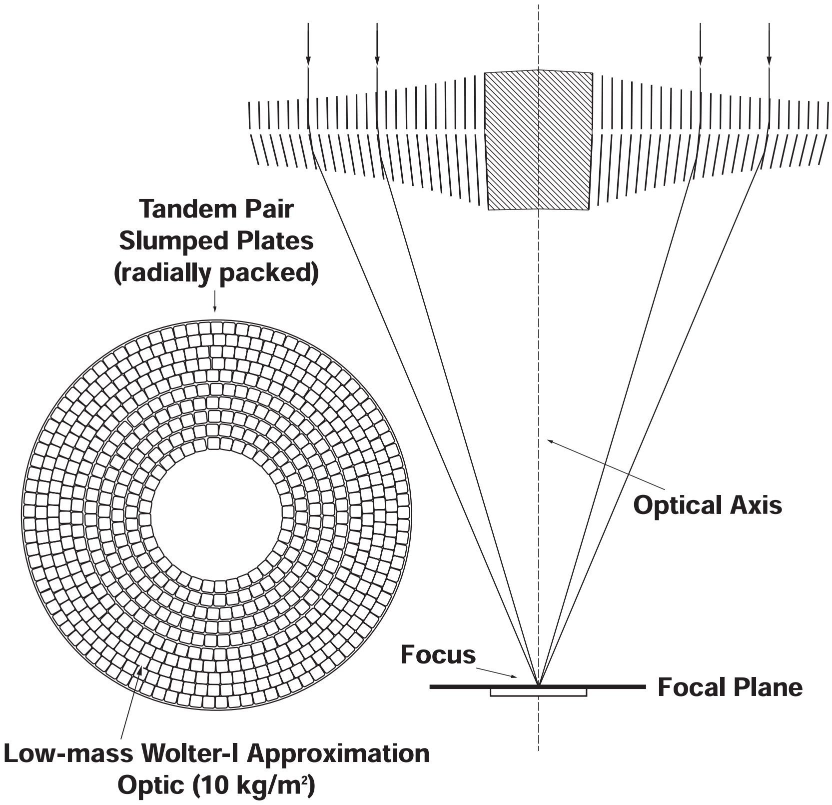

Figure 5. Schematic of an MCP-based optic. The microchannels are arranged in a radial geometry with a solid core. Two plates are required for the conical approximation of the Wolter-I geometry

A prototype X-ray optic consisting of two circular plates of 60 mm diameter, each 5 mm thick, was produced, as shown in Figure 6. Each plate contains 20 million almost perfectly square holes, each 10 microns in diameter, with a wall thickness of a micron. The MCP plates are made of glass with a high bismuth content, to increase the X-ray reflectivity and improve the processing of the glass. To achieve the conical approximation to a Wolter-I geometry, one plate is slumped to a spherical profile with a radius of curvature of 20 m, the other to a radius of curvature of 6.7 m. In combination, this doublet has a focal length of 5 m, which was chosen to facilitate X-ray testing. Figure 7 shows the hierarchical structure of the radially packed square multi-fibres in the MCPs of this optic. The RMS surface roughness is 10 A

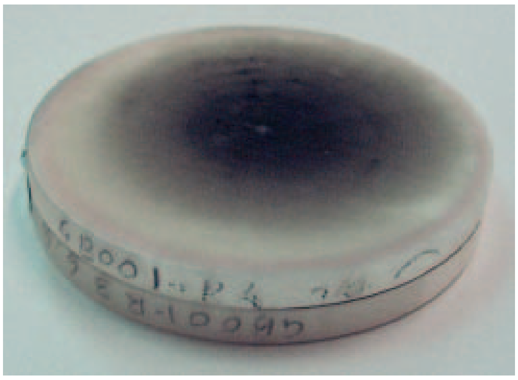

Figure 6. X-ray mirror doublet, conical approximation to a Wolter-I design - diameter 60 mm, thickness 2 x 5 mm, focal length 5 m. This is effectively an X-ray lens, analogous to its optical counterpart in the visible regime. Its mass is 28.5 g

(measured between 20 and 2000 mm^{-1}), which is sufficiently smooth to reflect medium-energy X-rays.

This X-ray optic behaves in the same way as a normal bi-convex lens in the visible range - it is effectively an X-ray lens. The lens is compact, robust, easy to mount and very light. The mass of the 60 mm-diameter prototype is 28.5 g (corresponding to 10 kg/m^2). This is to be compared with a value of ~900 kg/m^2 for XMM-Newton.

For practical optics of larger sizes, off-axis modules would be used. These are easier to fabricate because they require larger radii of curvature and are therefore more like the square-pore, square-packed MCPs.

The imaging quality and efficiency of the optics is limited by errors in the conical arrangement of the fibres in the plate.

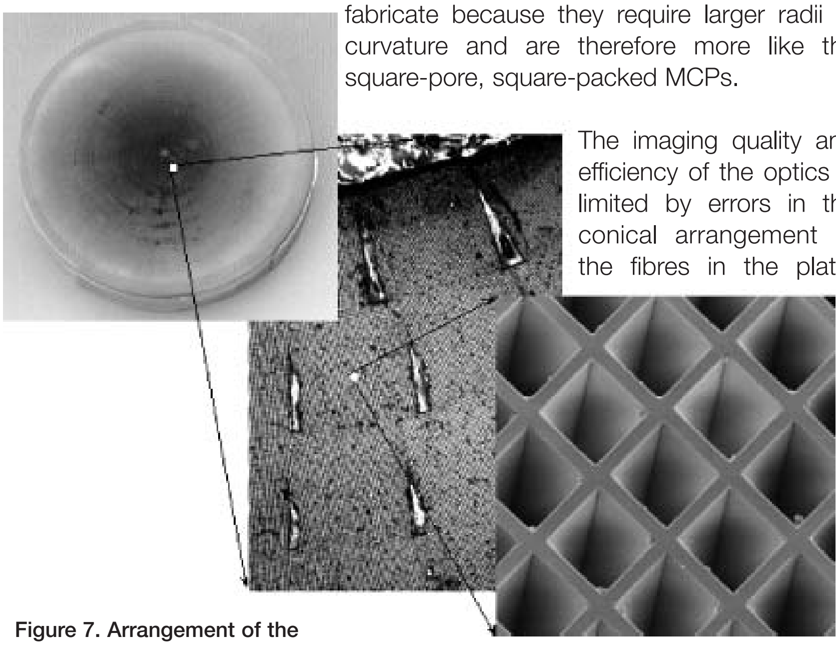

Figure 7. Arrangement of the square multi-fibre bundles in the radial stack for the doublet. Each square bundle consists of 55 x 55 single square fibres. The gaps between the bundles can be filled prior to etching the plates. The multi-fibre bundle size projects to 20 arcsec in the focal plane. The single fibres have pores of 10 x 10 μm^2

A misalignment of the pores in the first plate compared to the second plate can block part of the rays and blur the focus. Since the two plates of the doublet were cut adjacent to each other, most of the alignment errors are present in very similar amounts in both plates. Consequently, the errors in the two plates compensate each other to a large extent, and only increase the vignetting.

Figure 8 shows the first true image of a point-like X-ray source taken with the prototype MCP optics of a Wolter-I configuration at the ESRF facility. The X-ray radiation of the source located 20 m from the optics, emitting photons of 8 keV (0.15 nm), is focused by the glass X-ray lens. Half the focussed radiation falls within a circle with a diameter of 1.0 arcmin. This is only a factor of 4 larger than the imaging resolution of XMM-Newton, with a much larger specific mass (with 350 kg at a diameter of 700 mm, i.e. 910 kg/m^2). If this imaging quality were to be further improved, it might be possible to build an XMM-Newton comparable mirror system with a mass of ~10 kg, with accompanying savings in mission costs.

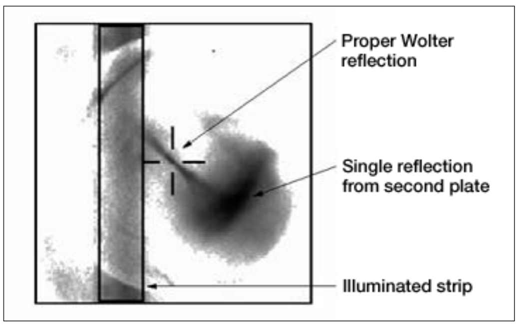

Figure 8. The first true X-ray image taken with the compact, MCP-based 'X-ray lens'. Only a strip of the optics is illuminated by the synchrotron radiation

Conclusion

A number of different technologies are being studied by ESA for the development of X-ray optics with a view to maximising the area/mass ratio whilst still maintaining image quality. The applications are very diverse, ranging from high-performance large-area mirrors, such as those required for the next generation of astrophysics missions such as XEUS and all-sky X-ray survey missions such as Lobster-IS, to very lightweight medium-resolution optics for planetary geology mapping through remote X-ray fluorescent imaging. Within this broad approach, MCP mirror technology is providing very attractive lightweight optics for mass-critical missions. Scattering and surface roughness are comparable to traditional X-ray optics, but the resolution is currently limited to about 1 arcmin. Square pores are used, which are perfectly square and straight at a level of 20 arcsec. The production of off-axis elements would allow the building of a segmented optic with a large diameter and collecting area. The challenge for Europe will be to pursue this and other novel technology further by improving the image quality and overall energy response.

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