Development of X-ray optics at ESA

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ABSTRACT

At the European Space Agency (ESA) X-ray optics are being developed for future astrophysics and planetary missions. The cosmology mission XEUS requires very large effective area X-ray optics with high angular resolution. This implies a large aperture for a single telescope system, which will necessarily require assembly in space from basic mirror modules known as petals. The technology for the implementation of this Wolter-I design is based on the heritage of the XMM-Newton optics, but requires substantial further research and development. With 6 m² effective area at 1 keV the XEUS optics is initially composed of 32 petals arranged in a circular aperture of 4.5 m diameter, compatible with single Ariane 5 launch into the XEUS orbit. Utilising the available infrastructure at the International Space Station (ISS) 96 additional petals, organised into 8 segments, are added to XEUS, increasing the effective area to 30 m². Key aspects of the XEUS optics are therefore low-mass design, industrialisation of the production, and ISS compatibility.

As a potential optics for a remote sensing X-ray fluorescence spectrometer, extremely low mass Wolter-I optics are being developed. Based on Micro-Channel Plates (MCP), the mirror thickness can be dramatically reduced, making an accommodation on such missions as the Mercury orbiter of BeppiColombo possible. With a resolution of about 1 arcminute and compact construction, such imaging X-ray optics are well matched to modern Si or GaAs based detector arrays and will allow the mapping of the planetary surface in fluorescent X-ray light with unprecedented sensitivity.

Keywords: X-ray astronomy, X-ray optics, Micro-channel plates, X-ray fluorescence analysis

1. INTRODUCTION

Europe has a strong heritage in X-ray optics (Exosat, Rosat, Beppo-SAX, XMM), and further evolution of the technology is required in order to satisfy the growing demands of the future. The main drivers remain the increase in angular resolution and effective area, and a reduction in specific mass.

Since there is no material that efficiently refracts X-rays, reflection optics are used for astrophysics and planetary space missions. The reflection occurs efficiently over a large range of photon energies only if the X-rays are reflected under grazing incidence with a small grazing angle (typically below 1 degree). The geometry of choice is mostly one of the Wolter configurations, with the Wolter-I preferred for mid-range X-ray energies (1 to 10 keV main bandpass). This leads to bulky and heavy optics if made from stiff mirrors, or poor imaging resolution if made from thin materials such as foils (in which case the conical approximation to the Wolter-I geometry is used). Only for very low X-ray energies and over a narrow bandpass are normal incidence X-ray optics with multi-layer coatings a practical alternative.

ESA together with European industry and research institutions is exploring the X-ray optics technologies for the next generation of space astrophysics and planetary missions currently under design. Two examples are discussed in this paper: XEUS [1,2,3,4] and BeppiColombo [5,6].

While the X-ray mirror technology used for XEUS is based on the heritage of ESA's cornerstone X-ray astrophysics mission XMM-Newton, a new approach is taken for X-ray remote sensing on planetary missions. In the later case, the technology used to produce glass micro-channel plates (MCP) is used to produce X-ray optics with very thin reflecting surfaces, of the order of only a few micrometer [7,8,9,10]. This results in a MCP optic that is far lighter and smaller than

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would be possible with conventional grazing incidence optics. As shown in figure 1, a conical approximation to the Wolter-I geometry is employed, and a radial geometry of the MCPs is required.

For the first time such a compact and light lens has been made in a geometry that produces true X-ray imaging.

Figure 1: Schematic geometry of a MCP-based optics. 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.

2. HIGH RESOLUTION OPTICS

The X-ray optics for the XEUS mission were designed to provide the effective area and angular resolution required by the science to be performed in the post-XMM-Newton and Chandra era. With the need to provide 30 m² effective area at 1 keV and 5 arcseconds angular resolution, with a goal of 2 arcseconds, an innovative mission scenario has to be developed and a suitable mirror technology found. Table 1 summarises the parameters, which influence the design of the XEUS optics.

The starting point for the mirror technology was the XMM-Newton nickel electro-replication technique. Due to the size of the XEUS optics a segmentation was required. The XEUS telescope will be constructed of units called petals, each about the size of one of the XMM-Newton mirror modules, and schematically shown in figure 2. The petals are off-axis segments of the telescope, each being integrated, tested and calibrated independently. Once in orbit, the petals are aligned with respect to each other using two linear actuators on each of the petals. Both celestial sources and an internal alignment metrology system are planned to be used for this operation.

Table 1: Design of the Wolter-I optic for XEUS

focal length	50 m
Geometry	Wolter-I with possibly integrated baffle extensions
Slot width	1.0 mm
Parabola length	0.50 m
Surface material	Au
RMS surface roughness	5 Å
Open core diameter	1.30 m
Outer diameter XEUS1	4.07 m
Outer diameter XEUS2	9.90 m
Fraction of circumference blocked by structure	10%

These parameters lead to a mirror nest that consists in the initial launch (XEUS1) of 296 mirror shells, where a shell is a surface of revolution that consists of both a parabolic and a hyperbolic part (as in XMM-Newton). The spacing of the smallest shells is 2.8 mm, and the spacing of the largest shells is 6.0 mm. After the extension sectors are added, the nest consists of 562 Wolter-I surfaces, with a spacing up to 13.3 mm. The mirror petals will contain integrated baffles to limit optical and X-ray stray light. To block single reflection X-ray stray light baffling rings could be used, such as on XMM-Newton. Alternatively each mirror plate could have an integrated cylindrical/conical extension that blocks single reflections. Such integrated baffles will also add two additional kinks in each mirror plate, which increases their stiffness.

Figure 2: The 10 meter diameter XEUS optics is assembled of units called petals, each containing about 100 mirror plates. Each mirror plate consists of a parabolic and a hyperbolic section. Each petal is aligned in orbit by the use of two linear actuators. The size of a petal is comparable to the size of an XMM-Newton mirror module (≤ 1 meter in each dimension).

By placing the X-ray optics on one spacecraft and the detector instruments on a second spacecraft, the focal length becomes a free parameter and may be chosen to optimise the performance and therefore the science return. The detector spacecraft

follows the focus of the telescope to within one millimeter, using solar-electric propulsion. The large focal allows the use of a single focal plane assembly, which improves the signal/noise ratio.

For XEUS2, the effective area at 1 keV remains constant to within 5% within the 5 arcmin field of view, as shown in figure 3, where the vignetting function at 1 and 8 keV, estimated from ray tracing, are plotted. At 8 keV the effective area is reduced by 17% at the edge of the field of view. For XEUS1 these numbers are 11% and 17% respectively.

The depth of focus differs largely between XEUS1 and XEUS2, and is in general larger for higher energies, as only the innermost mirror plates contribute significantly to the focus. Figure 3 shows the depth of focus based on a Monte-Carlo ray-tracing simulation of the response. The point marked 'geometrical' is determined from the path of the rays, disregarding the reflection coefficients. The depth labelled 1 and 8 keV take the reflection coefficients at these energies into account. The point marked 'high energy' corresponds to the geometrical depth of focus for the inner mirror up to a radius of 1.22 m, which corresponds to a grazing angle of 0.35° . Assuming that the reflectivity can be enhanced between 25 and 40 keV up to this grazing angle of 0.35° , this point corresponds to the depth of focus at 25 to 40 keV.

As is typical of Wolter-I optics, the image quality is reduced for larger off-axis angles. Figure 5 shows the increase in spot size at 1 keV as a function of the off-axis angle of a source.

Figure 3: The vignetting function of XEUS2, assuming gold coated mirrors.

Figure 4: The depth of focus of the XEUS mirrors. The half-energy width (the diameter of the circle that encloses 50% of the energy in the focal spot) as a function of the distance from the focal plane, based on ray-tracing the XEUS2 configuration with an optimum half-energy width (HEW) of 5". Shown is the geometrical HEW, which is obtained by disregarding the reflection coefficient, the diameter for 1 and 8 keV radiation, and an estimate for the depth of focus between 25 and 40 keV for a super-mirror coated optic, assuming a maximum grazing angle of 0.35°.

Figure 5: The half-energy width of the focus of XEUS assuming an optimum HEW of 5" or 2", plotted as a function of the off-axis angle of the source

3. LOW MASS COMPACT OPTICS

Instruments on planetary missions have so far been limited to (very) small effective area imaging X-ray optics, or more often, to collimator systems. The mass and compact size are the major drivers, and not so much the angular resolution. Effectively the specific mass has to be reduced by about a factor of 100, if compared to the XMM-Newton-technology. Currently the angular resolution is typically of the order of a degree, and a resolution of about 1 arcminute is to be regarded as excellent.

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

To adapt the MCPs for use as X-ray optics, it was necessary to change and improve the microfiber geometry and reduce further the surface roughness. The later was achieved by polishing the starting blocks of glass used to produce the fibers. The geometry was a larger challenge, since traditional MCPs are based on round fibers. For imaging applications square fibers are required, which in turn require modification to the drawing towers and the introduction of appropriate on-line metrology. The resulting optics is very rigid and extremely light. In fact the optics is also very robust, since the specific mass and the corresponding forces during vibration are low.

For an X-ray fluorescence mapper under study for the ESA Mercury mission BepiColombo, a 200 mm diameter MCP optics was designed. The cross section of such optics is shown in figure 6, and has a thickness that decreases with the radius of the plates. With this cross section, the optic becomes self-baffling. The proper shape of the optics surfaces is produced by grinding before the etching (and optional coating) of the MCPs. The thickness at the center of the plate is 40 mm, and 4 mm at the rim. The center 20 mm diameter is not used and simply blocked. The baseline focal length is 1000 mm.

Figure 6: Profile of baseline optics for the X-ray fluorescence mapper for BepiColombo. All sizes in mm. The proper shape of the surfaces can be achieved by grinding the MCP plates before etching and assembly.

The effective area of such an X-ray optics is shown in figure 7, as function of off-axis angle. Obviously, the effective area depends strongly on the surface material and the X-ray energy. A field of view of 2 to 3 degrees in diameter is achievable at 1 keV, dropping to less than 1 degree at 10 keV. A gold coating of the reflecting surfaces is clearly desirable, particularly for energies above 1 keV. Figure 8 shows the on-axis performance of such a system.

Figure 7: predicted off-axis performance of the MCP optics for BepiColombo. The optics consists of 4 rings, pore size is 50 micron, and the pitch is 60 micron.

Figure 8: On-axis performance, in terms of effective area, of the optics for the planetary mapper. The surface coating and base material strongly affect the high energy performance. Currently, samples are produced using the standard MCP glass type 297. Precursor tests were performed using lead glass and investigations into Au coating are being considered.

A prototype X-ray optics consisting of two circular plates of 60 mm diameter, each plate being 5 mm thick, was produced, and is shown in figure 9. Each plate contains 20 million almost perfectly square holes. The 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 of 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, the doublet has a focal length of 5 meters. Figure 10 shows the hierarchical structure of the radially packed square microfibers in the MCPs of this optics. The RMS surface roughness is 10 Angstrom (measured between 20 and 2000 nm^{-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 grams (corresponding to 10 kg per m^2).

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

Figure 9: X-ray mirror doublet, conical approximation to a Wolter-I design. Diameter 60 mm, thickness 2x5 mm, focal length 5 meters. This is effectively an X-ray lens, analogous to its optical counterpart in the visible regime.

The imaging quality and efficiency of the optics is limited by errors in the spherical arrangement of the fibers in the plate. A misalignment of the pores in the first plate as 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 a very similar amount in both plates. As a consequence, the errors in the two plates compensate each other to a large extent, and only increase the vignetting.

Figure 11 shows the first true image of a point-like X-ray source taken with the prototype MCP optics of a Wolter-I configuration. X-ray radiation of the source located at 20 m from the optics, emitting photons of 8 keV, is focussed by the glass X-ray lens. Half the focussed radiation falls within a circle with a diameter of 1.0 arcmin (0.017 degree). 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 per m^2).

Figure 10: Arrangement of the square multifiber bundles in the radial stack for the dublet. Each square bundle contains 55x55 single square fibers. The gaps between the bundles can be filled prior to etching the plates. The multifiber bundle size corresponds to 20 arcseconds in the focal plane. The single fibers have pores of $10 \times 10 \mu\text{m}^2$.

Figure 11: The first true X-ray image taken with the compact, MCP-based "X-ray lens" presented in this paper. Only a strip of the optics is illuminated by the synchrotron radiation.

4. CONCLUSION

Different technologies are being followed by ESA for the development of X-ray optics. The applications are very diverse, ranging from high performance large area astrophysics telescopes to very lightweight optics for planetary X-ray mappers. Currently available technologies are being further improved and new ideas are being developed and tested.

In the area of high resolution optics a significant increase in effective area is achievable with a single focal plane assembly by the use of off-axis elements (petals). Considering the large number of mirror plates and petals required, and the need for a stable and well controlled production, process automation and industrialisation will play a major role in this field. Nickel is, at this time, the best developed technology for lightweight large effective area X-ray optics, but alternatives may become interesting in future.

MCP technology is providing very attractive lightweight optics for planetary and other mass-critical missions. Scattering and surface roughness is comparable to traditional X-ray optics, but the resolution is currently limited to about 1 arcminute. 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 lens with a large diameter and collecting area.

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