The X-ray Evolving Universe Spectroscopy Mission (XEUS)

The X-ray mirror design and technology

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ABSTRACT

To achieve the demanding aims of XEUS, which involve the detection of sources as faint as 10^{-18} ergs cm⁻² s⁻¹ a large X-ray mirror will need to be developed. This core scientific aim implies that the XEUS mirror needs to have an effective collecting area at 1 keV of 30 m² coupled to a spatial resolution on-axis of between 2 and 5 arcsec (HEW), so as to avoid source confusion at these very faint flux levels. Finally a field of view of at least 5 arcmin must be covered so as to ensure that a significantly large population of high redshift x-ray sources can be observed in a single pointing over the energy band from 0.05 – 30 keV.

Clearly the key characteristic of XEUS is the large X-ray mirror aperture coupled to the high spatial resolution. The XEUS mirror aperture of 10 m diameter is divided into annuli with each annulus subdivided into sectors. The basic mirror unit therefore consists of a set of heavily stacked thin mirror plates each retaining the correct geometry. This unit is known as a mirror petal and constitutes a complete free-standing calibrated part of the overall XEUS mirror.

Key Words: X-ray Astrophysics, X-ray Mirrors, Future missions

1. INTRODUCTION

The primary scientific aims of XEUS: The X-ray Evolving Universe Spectroscopy mission is to study the astrophysics of some of the most distant and hence youngest discrete objects in the universe. The core scientific issues therefore that XEUS aims to address, can be summarised as follows:

- To measure the spectra of objects with a redshift z beyond 4 at flux levels down to 10^{-18} ergs cm⁻² s⁻¹.
- To determine from the X-ray spectral lines the redshift and thus age of these objects.
- To establish the cosmological evolution of matter in the early universe.

These general scientific goals for XEUS can be translated into the following specific requirements for the X-ray mirror:

- the telescope should cover a broadband from 0.05-30 keV with an effective collecting area of at least 10 m² at 1 keV and 1 m² at 8 keV [1]. This will ensure the spectra of objects from low to high z can be effectively observed.
- all the collecting area is to be focused into a single focal plane.
- a spatial resolution of better than 5 and preferably 2 arcsec [2].

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To place these demanding requirements in context figure 1 shows the collecting area at 1 keV plotted as a function of the half energy width (HEW) of the point spread function (PSF) at the same energy for various existing and proposed Wolter type I X-ray telescope modules. Triangles indicate foil mirrors (e.g. Astro-E), circles indicate replicated optics (e.g. XMM) and squares indicate monolithic shells (e.g. ROSAT). The horizontal lines correspond to the effective area required to collect 100 photons from faint sources of 10^{-14} , 10^{-15} , 10^{-16} and 10^{-17} ergs $\text{cm}^{-2} \text{s}^{-1}$ (0.5- 2 keV) in a 10^5 second exposure. The slanting dotted lines indicate the effective area required to achieve a 5 sigma detection in 10^5 seconds in the background limit when with significant diffuse counts confused with the source counts. The vertical lines indicate the approximate confusion limit for point sources estimated using the logN-logS derived from deep ROSAT PSPC exposures [2]. The best performance in terms of source identification in a deep exposure is achieved for mirror modules that are close to the intersection of the horizontal and vertical lines.

Figure 1: XEUS in context with previous and current missions. The collecting area at 1 keV is plotted against the resolution (HEW, at 1 keV) of the optics. Triangles, circles and squares indicate foil-, replicated and monolithic mirror technologies, respectively. Note how the XEUS II configuration ensures that faint objects can be detected and resolved effectively from other objects in the field.

The largest collecting area yet achieved from an X-ray mirror system focusing into a single image is the 1400 cm² at 1 keV of the XMM mirror modules [3] and the best angular resolution is 0.5 arcsec for Chandra (AXAF). The primary aim of XEUS is to perform spectroscopy on the faint sources only accessible in the top left-hand quadrant of the figure. Two XEUS points are shown, XEUS I and XEUS II. The first is the configuration after the first launch and the second is achieved after the mirror expansion in orbit. For details on the mission scenario see the dedicated paper elsewhere in these proceedings. The angular resolution of XEUS must be at least 5 arcsec HEW to avoid confusion from sources with fluxes below $\sim 10^{-16}$ while a goal of ~ 2 arcsec HEW is obviously advantageous particularly at even fainter levels. XEUS demands an enormous leap of a factor of 70 in collecting area over XMM whilst at the same time the angular resolution must be improved considerably.

2. OPTICS DESIGN

2.1. Single focal plane

The XEUS telescope concept consists of a single mirror system and a single focal plane. In principle the same area and angular resolution could be achieved using a large number of parallel XMM size telescope modules each with its own focal plane. There are definite advantages to the XEUS approach:

- improved signal to noise
- minimises number of focal planes
- simpler calibration at system level

whereas the disadvantages are

- reduced redundancy
- more demanding optics
- complex single focal plane

As we shall discuss below, the large area can only be realised using a large number of modules, whichever strategy is adopted.

2.2. Design criteria

The following are the important factors in the design of grazing incidence X-ray reflective optics:

- The total surface area of the reflecting surfaces. Focussing X-ray requires sub-nanometer roughness of the surfaces. To obtain the required angular resolution the figure should also be well controlled (albeit not so accurately as would be required for an optical telescope). Furthermore the total area of the reflecting surfaces will determine the mass of the optic. A possible parameter that can be used to characterise the optics is the surface utility: the ratio of the effective area to the total reflective area.
- The degree of replication and nesting that is possible. Replication reduces the number of surfaces that have to be polished to the required figure and roughness accuracy.
- The overall size of the optic. Traditionally this is limited by the diameter of the launch vehicle and possible extension mechanisms as well as the costs of tools required to fabricate the optics. The advent of the International Space Station might allow assembly of the optic in space, such that this criterion might be of less importance than the total area of reflecting surface. A useful characterisation of the effective use of the limited size is the aperture utility defined as the ratio of the effective area to the geometric area of the aperture.
- The spectral response of the optic. It is possible to achieve large reflection coefficients in a somewhat narrow energy band using multilayers. Given the broadband requirements of XEUS it is however important to take into account the energy bandwidth of the optics which is set at 0.05-30 keV.

All the large imaging soft X-ray telescopes flown to date have employed Wolter type I optics or approximations thereof. Figure 2 shows the aperture utility at 1 keV for the Wolter I modules (existing and proposed) included in figure 1. Foil mirrors are labelled with triangles, replicated mirrors by circles and monolithic shells by squares. An aperture utilisation of 10 and 50% are shown as horizontal dotted lines. It is unlikely that any grazing incidence system could achieve better than ~50% because of the necessary shell thickness, support structure and the Fresnel reflectivity of high Z materials. All the monolithic shell modules have a utilisation of below 10% although they all have better than 12 arcsec HEW. Such shells must be relatively thick so that high figure accuracy and polish can be achieved. Foil mirrors give high aperture utilisation but cannot be manufactured with high figure accuracy and therefore they all have a HEW significantly worse, typically above 60 arcsec. Replicated mirrors fall in between. The EXOSAT mirrors were not highly nested and therefore did not achieve high aperture utilisation. The XMM mirrors have the highest aperture utilisation yet realised. The XEUS point shown corresponds to the design proposed below. It demands the highest possible aperture utilisation coupled with relatively high angular resolution. This is a clear challenge for the XEUS mirror development program.

Figure 2: The aperture utility as figure of merit for existing and proposed X-ray telescope optics vs. HEW at 1 keV for Wolter I and approximations thereof.

2.3. Wolter-I surfaces

For the overall XEUS telescope in both its zero growth (XEUS-1) and fully-grown (XEUS-2) configurations the baseline design parameters are summarised in table I.

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

Focal length	50 m
Slot width	1.0 mm
Parabola length	0.5 m
Hyperbola length	0.5 m
Surface material	Au *
Shell thickness	<0.5 mm
Shell material	Ni or Ni composite
RMS surface roughness	5 Angstrom
Open core diameter	1.3 m
outer diameter initial launch	4.2 m
outer diameter after extension	9.7 m

* This coating will be further optimised as a function of shell radius (at petal level) and hence graze angle later in the XEUS mirror development program.

These parameters lead to a mirror nest that consists of 306 mirror shells for XEUS1 and 535 mirror shells for XEUS2, where a shell is a surface of revolution that consists of both a parabolic and a hyperbolic part. The spacing between the smallest shells is only 2.8 mm, while the spacing of the largest shells is 13 mm.

The shell thickness must be less than 0.5 mm to provide the high aperture utility shown in figure 1 and reduce the total mass of the shells. Yet these thin shells must be manufactured with high figure accuracy and with very low surface roughness. They must of course be stiff enough so that they can be integrated and aligned into a Wolter I nest with high accuracy and without undue distortion from handling or gravity.

2.4. Coating

Although gold was used for the XMM mirrors, other materials were investigated for potential advantages in the case of XEUS. Figure 3 shows a summary of the results specifically for the XEUS geometry. Although different materials show clear improvements for specific energy ranges, gold is reasonably well matched to the scientific requirements discussed in section 3. As the XEUS petal development program establishes the constraints in the fabrication process the optimisation of the reflective coating against petal position within the overall mirror will be further studied.

Figure 3: The optimum surface utility as figure of merit of different mirror coating materials.

3. SEGMENTED MIRROR

In order to manufacture the XEUS optics, the mirror has to be broken down into units, which can be manufactured at reasonable cost, handled and tested in a way comparable to traditional X-ray optics of today. The key for building the optics for XEUS is the segmentation of the optics into independent units known as petals. Figure 4 shows schematically the principle: the X-ray mirror no longer consists of concentric closed electroformed shells (like XMM), but of open plates, which cover only a fraction of the complete circle. These mirror plates are mounted in a petal structural box, which forms a rigid optical unit, small enough to be handled in a manner similar to a fully integrated XMM mirror module.

Each mirror petals is mounted on an optical bench, which forms part of the mirror spacecraft (MSC) structure. The petals are connected to the optical bench via translators, which allow the individual mirror petals to be aligned in-orbit in respect to each other. Therefore the requirements with respect to rigidity and deformation of the mirror under the launch loads etc is mainly restricted to the individual petals. The requirements placed on the complete optics as a whole, i.e. the 4- 10m diameter precision mirror, is less stringent, since any deformations of the optical bench or mounting mechanisms can be compensated for in orbit. The inter-alignment of the petals will be done using a dedicated alignment system and will then be confirmed using known astrophysical sources.

Figure 4: Mirror plates are mounted in mirror petals that are aligned in orbit.

Figure 5 shows the arrangement of the mirror petals that make up the optics of XEUS I – the initial zero growth XEUS mirror spacecraft (MSC1). A solar array and a reaction control system are placed around the outer surface of the second ring of petal. The petals are arranged in two rings of 16 petals each around the central core of the spacecraft. There, well insulated from the mirror petals, the MSC bus is located. The inner ring of petals provides the high energy response of the telescope, but is, at the same time, the most expensive in terms of mirror production due to the small incidence angles and the unfavourable surface utility.

Figure 5: Optics of XEUS I, segmentation into 16+16 petals

After XEUS I has completed its initial observations primarily of objects at redshifts below $z \sim 4$, (~4 years into the mission which has a total duration of over 25 years) the MSC will visit the International Space Station (ISS) so that the mirror can be expanded. Essentially it is grown to become XEUS II; the growth is from a 4.5 m diameter optics to 10 m. Due to the modular construction of the XEUS mirror, effectively only new petals have to be added to the periphery of XEUS I (figure 6). In order to facilitate the build-up at the ISS, the petals are organised into 8 sectors of 4x3 petals each. Again the alignability of the individual petals will provide sufficient tolerance to integration errors unavoidable during the build-up. This design is crucial for the growth of the XEUS mirror coupling realistic petal fabrication procedures to logistical and operational constraints of growth at the ISS.

Figure 6: Optics of XEUS II, consisting of optics of XEUS I with the addition of 8 sectors of 12 petals each.

4. MIRROR PRODUCTION

The individual mirror plates that are mounted in the petals must have both a very accurate figure and excellent surface roughness. The technology used to produce the XMM mirror shells has proven that electroformed mirror shells can be very accurate reproductions of the mandrel on which they are produced, provided the correct production process is followed meticulously. The XEUS mirror development program has already demonstrated that also open surfaces (the petal plates) can be produced by this method.

The production process had to be optimised for the specific XEUS petal requirements and to this end a numerical (Monte Carlo) simulator is under development. Reduced size plates (with the XMM focal length of 7.5 m) have been fabricated to enable the use of the test facilities used for XMM with only limited modifications. These plates allow rather quick validation of measured performance against simulator predictions. The test plates were measured with optical and mechanical metrology tools. It has now been demonstrated that plates can be produced which have figure errors small enough to produce a focus with a half-energy width of 3.5 arcsec as determined from optical metrology. The mirror plates were 'freely' supported during the measurements. The surface roughness is an exact copy of the roughness of the mandrel employed. The mirror plate thickness could be made small enough to be compatible with the available launchers foreseen for XEUS. The mirror plates proved to be quite robust and easy to handle (figure 7).

After fabrication through the nickel electroforming process, the mirror plates are inspected for defects and surface roughness and geometric shape is measured. The mirror plates are then one by one integrated into the petal structure using active alignment methods. Once the correct shape and location of the plate is established, each mirror plate is locked in position by a gluing process. The materials of the mirror plates and of the petal structure must of course have very similar coefficients of expansion, in order to allow for a sufficiently large range of operating temperatures without image degradation. Due to the nature of an open surface, certain figure errors can be removed during integration, without significantly affecting other parameters that control the figure. This is clearly not the case for closed shells such as those used for XMM. This compensates in part some of the difficulties arising from the reduced symmetry of the open plates.

Finally finite element methods are being employed to establish the most appropriate mounting scheme for these large mirror plates. In addition the tolerances to be expected during integration of the plates were determined and the error budgets established.

Figure 7: XEUS mirror plates, gold-coated electroformed nickel.

In parallel, investigations have been made regarding the production of full-size mirror plates so as to study the mechanical behaviour of these optical elements. Although these tests are still ongoing it is possible to conclude that full-size mirror plates of the correct shape for XEUS (i.e. 50m focal length, thin-walled, 1/8 and 1/16 segments) are also possible to fabricate (figure 8).

Figure 8: Full size structural thermal model mirror plates. To give an idea of the scope of the XEUS mirror program it must be noted that these plates would form only part of the inner most petal of XEUS-1. For comparison an XMM mirror shell is shown in the centre.

5. CONCLUSION

In conclusion the fabrication of optics that meet the requirements established at the beginning of the XEUS program appear to be achievable. The preliminary hardware activities coupled to detailed numerical simulations have given some confidence that the design is realistic. In the mid-term future test facilities will have to be developed that can provide the necessary accuracy and accommodate the dimensions of the XEUS petals, particularly in the UV and X-ray regime.

Finally the effective area that can be achieved with this technology is shown in figure 9 as function of X-ray energy. For illustration the effective area function for a micro-channel plate optic (MCP), which is compatible with the XEUS parameters and could be used as a hard X-ray extension, is also plotted.

Figure 9: Effective area of the XEUS I and XEUS II optics. Additionally the response of XEUS compatible MCP optics is shown.

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7. REFERENCES

1. Turner M.J.L., Watson M.G. (eds.), The Next Generation of X-ray Observatories, Special Report XRA97/02, ISBN 0 9530183 0 X, 1997
2. Hasinger G. et al. Astronomy & Astrophysics 275, 1-15, 1993
3. Chambure, D. de, Laine R., van Katwijk K. van Casteren J. and Glaude P., Producing the X-ray Mirrors for ESA's XMM Spacecraft, in ESA Bulletin 89, ISSN 0376-4265, Feb. 1997