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Status of the optics for the X-ray Evolving Universe Spectroscopy Mission (XEUS)

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ABSTRACT

The X-ray optics for the X-ray Evolving Universe Spectroscopy Mission (XEUS) have to satisfy the demanding requirements of this ambitious mission. XEUS is under study at the European Space Agency in the frame of the Horizon 2000+ program, utilizing the International Space Station (ISS) to take X-ray astrophysics into a new era. In a single launch XEUS1 is brought into orbit and deployed, providing a 4.5 m diameter X-ray optics with an angular resolution of 5 arcseconds. After a pre-cursor phase of astrophysical observation the XEUS mirror spacecraft docks to the ISS and is there significantly expanded, whereby the effective area of the optics is increased by a factor of 5, reaching 30 m². This servicing at the ISS is based on the currently foreseen capabilities of the ISS and strongly relies on robotics and the presence of astronauts.

The progress in developing the X-ray optics for XEUS is reported. Based on electro-formed mirror plates, which are mounted into mirror petals, the optics is modular and elegantly breaks the size limitation dictated by current designs. The necessary high level of control of the Nickel electroforming process is based on the legacy of the XMM project, launched by ESA in December 1999, but substantially improves the angular resolution and the collecting area. New materials are being explored for the fabrication of the high precision Wolter I shaped mandrels, scaled model petals are being made to study the X-ray imaging properties, and full-scale structural models are built to confirm the numerical evaluation of the optics and engineering designs. Appreciable progress has been achieved on the X-ray optics, supporting the system level and feasibility studies of the mission, which are aimed at proving the feasibility of the novel concept of XEUS.

Key Words : X-ray Optics, Astrophysics, Future missions, International Space Station

1. INTRODUCTION

With the advent of the modern high-resolution X-ray spectroscopy missions Chandra [1] and XMM-Newton [2] a new horizon is opening to the exploration of the universe. During their expected operational lifetime of about a decade these observatories will answer many questions and open new ones, which will require even more sensitive instruments for their resolution. Cosmology and the study of the evolution and structure of the universe will require highly sensitive observations of both the cold and the highly complementary hot baryonic matter at large distances. Missions like NGST, FIRST and ALMA will address the study of the cold matter, while an equally sensitive X-ray is required to observe the formation of objects like super-massive black holes at high redshift, $z > 5$, and hot inter-cluster gas in rich clusters of galaxies. The starting point in the design of XEUS is the requirement to achieve sufficient sensitivity in the X-ray band to complement the observations at lower photon energies by other observatories (see figure 1).

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In order to discover and spectroscopically study such objects with X-ray luminosities in the range 10^{43} to 10^{44} erg/s at distances $z > 5$, a spectroscopic effective area of 20 m² is required below 2 keV (see figure 2)[3]. Due to the high redshift of such objects the most prominent emission lines get shifted into this energy band.

Figure 1: Cosmology and the study of the evolution of the universe and the organization of matter into stars, galaxies and black holes requires the observation of both cold and hot matter. XEUS is designed to observe the hot matter with a sensitivity matching that of the missions foreseen to study the cold universe.

Figure 2: The ability of XEUS2 to detect and measure the properties of massive primeval black holes, compared to that of XMM-Newton.

At such depth of observations an angular resolution of between 2 and 5 arcseconds is required to minimize effects of source confusion and the diffuse galactic background [4].

These two requirements led to the design of the XEUS mission, featuring a 10 meter diameter X-ray telescope with 50 meters focal length that provides sufficient collecting area in the energy band < 2 keV. Though not a driver, considerable sensitivity and therefore large effective areas are also required at higher X-ray energies: 3 m^2 at 8 keV is called for.

To achieve the required sensitivity with such an optics still very demanding detector technology is needed. Energy resolutions of 2 eV and 5 eV are required at 1 keV and 8 keV, respectively.

2. THE XEUS TELESCOPE DESIGN

The XEUS telescope and mission design is based on three ideas:

- **Assembly in space and the utilization of the International Space Station (ISS)**

In order to be able to achieve an angular resolution of at least 5 arcseconds with an aperture of 10 meter diameter, a mission concept was developed for XEUS, whereby the ISS is used to assemble the X-ray telescope in space [5]. Although the X-ray mirror shell thickness could be significantly reduced from that used in the XMM-Newton telescope [6], while actually increasing the angular resolution, the total mass of the XEUS optics is still driven by the high angular resolution required. Due to the low earth orbit chosen for XEUS, and the associated large launch capabilities, only two launches are required to lift the XEUS optics into orbit. In order to be cost effective, the assembly of the 10 meter diameter, high resolution X-ray mirror in space requires an existing complex infrastructure in space: the ISS.

- **Separate mirror and detector spacecraft and a large focal length**

Due to the small reflection angles for X-rays, a large focal length is required for a broad band large area telescope. Considering the complexity and high cost of state-of-the-art detector spectrometers, involving cryogenic temperatures in the milli-Kelvin range, a single focal plane assembly is highly preferred. The XEUS concept therefore separates the mirror from the detector instruments and places them on two different spacecraft. The focal length may therefore be optimized according to the astrophysical requirements and the nature of X-ray physics [7]. The optics is placed on the Mirror Spacecraft (MSC) and the detector instruments [8] of XEUS on the Detector Spacecraft (DSC), see figure 3.

In addition this concept allows for the simple replacement of the focal plane instruments and critical spacecraft systems by exchanging the smaller but much more complex detector spacecraft. It becomes possible to consider and profit from the observed fast pace in detector technology improvement without replacing the optics. The X-ray mirror lifetime in space is very long, but the mirror is very expensive in production and launch costs. The X-ray optics constitutes the largest fraction of the XEUS mass, and the associated mirror spacecraft is rather simple and can be designed for a long lifetime.

- **Modular optics and petal alignment in orbit**

The optics of XEUS is modular, dividing the optics into annuli and sectors, providing units ('petals') which are easy to handle during production, alignment and characterization, of less than $1 \times 1 \times 1 \text{ m}^3$ in size. These petals are aligned in relation to each other in orbit during the commissioning phase. The optics of XEUS1, launched and deployed by an Ariane 5, consists of 32 petals and has a diameter of 4.5 meters with an effective area of 6 m^2 at 1 keV and 3 m^2 at 8 keV.

The implementation of these ideas resulted in the following XEUS mission scenario, which is shown schematically in figure 4:

XEUS1 is launched in a single Ariane 5 launch. After separation, the MSC flies an inertial orbit, slowly spinning for thermal control. The MSC is pointed to the target on the sky and communicates its housekeeping data to the DSC, which

then forwards the information to ground. The DSC utilizes solar-electric propulsion to keep its non-Keplerian orbit following the focal point of the telescope at 50 meters distance from the MSC, as shown in figure 3. The attitude of the DSC is controlled conventionally via startrackers and the attitude is therefore kept in relation to the sky. The orbit control system on the other hand measures the relative position to the MSC, using an optical tracking system and DGPS. The detectors are positioned with an accuracy of ± 1 mm onto the nominal focal position in all three axes. For about 50% of the time observations take place above the dark earth, using the earth as a sun shield.

Figure 3: The XEUS1 Detector Spacecraft (DSC1) is positioned at a distance of 50 m from the Mirror Spacecraft (MSC1). The two spacecraft are deployed in a single Ariane 5 launch and feature an effective X-ray optics area of 6 m² at 1 keV and 3 m² at 8 keV. The MSC1 mirror consists of 32 petals, which are actively aligned in orbit. The concept of XEUS allows the replacement of the detector instruments at regular intervals by a simple replacement of the DSC, keeping pace with the evolution of X-ray spectrometers.

After about 4 years of operation of XEUS1, the MSC docks to the DSC, thereby demonstrating the maneuvering and docking system prior to the visit to the ISS. With the efficient propulsion system of the DSC1 the coupled pair lowers the orbit to that of the ISS and is then able to wait for a period of up to one year outside the safety zone of the ISS until the latter is ready for the visit. At this time DSC1 is de-orbited and MSC1 docks to the ISS, where the X-ray mirror is expanded to a diameter of 10 meters, increasing the effective area by a factor of five.

The mirror elements required for the upgrade of MSC1 to MSC2 are organized in eight sectors, each containing 12 petals. These sectors also include new MSC subsystems, particularly the AOCS units and electronics, significantly extending the lifetime of the spacecraft. All mirror petals are protected from contamination by doors, which are opened only in the observation orbit. The launch of the eight mirror sectors including the transport carrier structure to the ISS can be accomplished with a single launch of the Space Shuttle, although alternative cargo carriers are also under study.

The ISS activities required by XEUS are based on the foreseen capability, infrastructure and resources of the ISS. The transport of the mirror sectors on the ISS and their integration onto the MSC1 is performed by the large main ISS robot SSRMS and the European Robotic Arm ERA. The mirror sectors are equipped with fast locking mechanisms which provide the necessary rigid connection of the mirror sector optical bench to that of the MSC1, while being compatible with the robotic integration. The integration process relies on the presence of astronauts in the ISS, but extravehicular activities are minimized, being limited to inspections and contingencies. The XEUS mirror growth at the ISS requires about two weeks, after which the MSC2 is ready to leave the ISS. Figure 5 shows the integration of a mirror sector onto the MSC1 by

the ERA, with the mirror sector carrier being presented by the SSRMS. Note the stored solar baffles on the back of each mirror sector, which are deployed and secured when the MSC2 is still at the ISS.

Figure 4: The XEUS mission scenario. The 4.5 meter diameter X-ray optics of the XEUS1 is increased to a diameter of 10 meters of XEUS2 by the addition of 8 mirror sectors. The first observation phase extends over about four years, whereas the mirror growth at the ISS is accomplished in a couple of weeks. XEUS1 could be launched by the end of the decade, with XEUS2 starting the second observation phase in 2015, within the ISS Design Lifetime. (Graphics: courtesy DASA.)

After completion of the MSC2 integration and testing, MSC2 separates from the ISS and DSC2 is launched. DSC2 is equipped with a new generation of better performing detector systems, which should be available four years after DSC1. The provision of a new DSC and the simple replacement of the instruments and DSC spacecraft systems by spacecraft maneuvers, and not by mechanisms, effectively allows the use of the high quality, large and long-lived inert X-ray optics for a very extended period of time. If DSC2 becomes unreliable or fails, DSC3 replaces the instruments with yet a better version, together with more evolved spacecraft subsystems.

An important factor in the XEUS schedule is the ISS Design Lifetime, which is 10 years. The ISS must be completed at the time of the XEUS visit, and the MSC expansion must be completed before the end of the ISS Design Life. The launch of XEUS1 could occur within a decade, corresponding to the expected lifetimes of Chandra and XMM. With the expected duration of the first observation phase of XEUS1 being four years, the XEUS schedule is in line with that of the ISS.

Figure 5: Integration of mirror sectors onto MSC1 by the ISS robots, increasing the effective X-ray mirror area of XEUS by a factor of five to 30 m² at 1 keV. A single space shuttle launch is sufficient to uplink the eight mirror sectors to the ISS.

MIRROR TECHNOLOGY

The XEUS X-ray optics technology is based on the nickel electro-replication method developed for XMM-Newton [6]. The latest mirror modules made for the XMM program achieved 11.7 arcsecond HEW and 4.9 arcsecond FWHM with a very symmetric point spread function. With an outermost diameter of 700 mm the mandrels required for XMM were large, but still manageable. The size of the XEUS optics prohibits the use of closed mirror shells, both for cost reasons and mechanical stiffness. The basic element of the XEUS X-ray telescope is therefore a mirror plate, which is a sector of such a shell. Figure 6 shows three mirror plates made by a variation of the XMM mirror production process. These plates were made using refurbished and upgraded XMM mandrels and are much thinner and therefore specifically lighter than the XMM shells. With the technology at a very high standard just after delivery of the XMM flight modules and the availability of the XMM mandrels, the mirror technology could be evolved rapidly towards the requirements of XEUS. Effectively at 1:3 scale of a typical XEUS mirror plate, the available metrology and assembly tools could be used with minor modifications. The scaled mirror plates proved very useful in the development of the alignment and integration techniques to be used for XEUS. Mirror shells of very uniform thickness and low residual material stress are routinely produced, with surface roughnesses of below 5 Å and HEW of less than 4 arcseconds in a free-hanging configuration as measured in an optical Hartman test.

Simultaneously numerical finite element models were developed to study the properties of full scale XEUS mirror plates, having a 500 mm long parabolic and a 500 mm long hyperbolic section. Also included in these models were the integrated mirror baffles foreseen for the XEUS optics. The effects of material thickness, gravity, support schemes and integration methods, handling procedures etc were simulated and optimized. In figure 7 an example is given for the calculated distortions of a full size XEUS mirror plate supported on each side at five discrete non-optimized positions. The distortions induced by the support system translate into a HEW of only 1.4 arcsecond.

The electro-forming process of full-scale mirror plates was optimized using full size mandrels with a good mechanical finish, but no superpolish. Issues like thickness uniformity, process optimization and control as well as tool development were addressed. One of the results is shown in figure 8, where the mirror plate thickness is plotted as function of the position on a full-size XEUS plate. The thickness non-uniformity is less than 3% of the plate thickness, which in this case is 0.5 mm.

Figure 6: The XEUS X-ray optics consists of mirror plates, organized into mirror petals. The plates shown are 1:3 scale with X-ray quality finish. At 150 to 300 μm thick, depending on the radius in the XEUS aperture, their mass is compatible with the XEUS scenario and the capabilities of the foreseen launchers.

The integration of mirror plates into support structures is being further optimized, considering also the stacking requirements for the XEUS petals. The petal structure will be made of the same material as the mirror plates, by identical processes, i.e. electro-forming off dedicated mandrels. Deformations due to differential expansion will thereby be minimized.

Figure 7: Finite element analysis of a full size XEUS mirror plate. The plate is supported by five discrete points on each side, but the locations of the support points is not optimized. Nevertheless the distortion induced by the support is no more than 1.4 arcseconds HEW.

Figure 8: The thickness non-uniformity of a full size XEUS mirror plate is less than 3% of the plate thickness.

3. MANDREL FABRICATION

A major component in the fabrication of high quality X-ray mirror plates by electro-forming are the mandrels used to define the figure and surface finish of the optics. The mandrels must be superpolished, have the required figure quality and temporal stability (a lifetime of a few years is needed without deformation) and be compatible with the mirror plate production processes. The mandrel technology used for XMM, based on aluminium cores with nickel coating, is likely not applicable for the industrial production of the large number of higher quality mandrels and mirror plates required for XEUS. Creeping of the base material is one of the major concerns. A study was undertaken to analyze the possible options for the base material to be used for the XEUS mandrels. Zerodur appeared as the most promising candidate, providing a very uniform material with a very small thermal expansion coefficient. Significant experience exists with the machining and polishing of Zerodur.

A prototype XEUS mandrel was produced to demonstrate the feasibility of the production of such mandrels to the required accuracy, and to provide a tool for further work on the production of mirror plates [9]. The resulting mandrel is shown in figure 9.

With a focal length of 50 meters and a true monolithic Wolter-I shape and X-ray level finish, the mandrel is representative of the expected production series XEUS mandrels. For compatibility reasons with the mirror plate production and testing facilities currently available, the length of the mandrel is slightly reduced to 600 mm (optical area). The measured HEW is limited by the metrology and is better than 2.4 arcseconds. Surface roughness is less than 0.38 nm, and the polishing defect density is very low at less than 0.05% of the area.

Figure 9: XEUS Wolter-I mandrel with 50 m focal length, made of Zerodur.

4. CONCLUSION

By the end of this decade XEUS will be able to extend the spectroscopic study of the universe to the origins of hot matter, a mere billion years after the big bang. Based on a novel approach to the X-ray astrophysics space mission design and the perfection of the XMM-Newton X-ray optics technology, XEUS proves to be a feasible mission to succeed XMM-Newton and Chandra immediately after they end their operational lives. By utilizing the extensive and complex infrastructure offered by the International Space Station, the XEUS X-ray optics can be built to the required diameter of 10 meters. Due to the large launching capacity of the Ariane 5 into the XEUS orbit of about 18 tons, the X-ray mirrors can be made sufficiently massive to achieve the required angular resolution of 5 arcseconds.

The recent development of the XEUS X-ray optics focused on the experimental confirmation of finite element studies of the mirror shell properties. It could be shown, that the figure errors accounted to gravity effects, intrinsic stiffness and mounting forces and torques can be controlled to the levels compatible with the XEUS requirements.

The nickel electro-replication processes were optimized for XEUS full-scale mirror plates, resulting in excellent mirror plate thickness uniformities and low residual stress levels. The production of 1:3 scale mirror plates also continued to improve, supporting the mirror support and integration activities.

A high quality mandrel was produced, which will be used in the next phase of the XEUS optics development program. After an extensive evaluation of possible base materials for this mandrel, Zerodur was selected, particularly due to the very demanding figure stability requirements over time-scales of years. The mandrel was a true Wolter-I shape with a focal length of 50 meters and is superpolished to the XEUS requirements.

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