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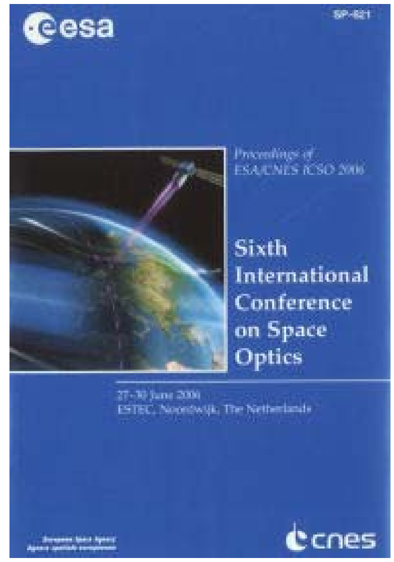

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ESA STUDY OF XEUS, A POTENTIAL FOLLOW-ON TO XMM-NEWTON

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ABSTRACT

In October 2005, based on a massive response by the Science Community to ESA's call for themes in space science, a large aperture X-ray Observatory (XRO) was identified as a candidate project for Europe within the frame of the 2015-2025 Cosmic Vision program [1]. Such a mission would represent the natural follow-on to XMM Newton, providing a large aperture X-ray telescope combined with high spectral and time resolution instruments, capable of investigating matter under extreme conditions and the evolution of the early universe.

The paper summarises the results of the most recent ESA internal study activities, leading to an updated mission configuration, with a mirror and a detector spacecraft flying in formation around L2 and a consolidated scientific payload design. The paper also describes the ongoing technology development activities for the payload and for the spacecraft that will play a crucial role in case ESA would decide to develop such a mission.

1. INTRODUCTION

Preliminary studies on a post XMM-Newton mission (indicated as XEUS, X-ray Evolving Universe Spectroscopy) assumed a LEO scenario, with two S/C's in formation flying, 6 m^2 (at 1 keV) effective area mirror and a focal length of 50 m. The mirror optics was originally based on the same technology used for XMM (replicated nickel mirrors), while the mission scenario was assuming a multiple launch approach and the use of ISS as servicing post for the observatory.

In September 2003, ESA investigated non-ISS related scenarios, focusing on the adoption of an innovative optics technology (Silicon High precision Pore Optics – Si HPO) and on an even larger observatory (effective area of order 10 m^2 at 1 keV) at L2. This new configuration triggered the interest of the US scientific community, resulting in a joint ESA/JAXA/NASA effort. A number of activities have been performed on this mission profile, including dedicated CDF studies, both at ESA and NASA [2]. The profile was again assuming a formation flying approach, with a deployable mirror supported during launch by a dedicated canister. Baselined LV was Ariane 5 or Delta-IV Heavy. Although the study activities were conducted in collaboration with NASA, differences remained in the overall configuration, especially on the Mirror Spacecraft (MSC) side, due to different model payload assumptions (including the addition of reflection gratings behind some parts of the mirror).

Following the decision of NASA to suspend collaboration on a joint study, ESA and JAXA have jointly started in the third quarter of 2005 a revision of the mission configuration, aimed to remain compatible with the available level of resource and reduce development risks and time.

The revised XEUS mission scenario described in this document is based on an A5 launch to L2, a composite S/C composed by Detector (DSC) and Mirror (MSC) unit inserted as a single stack into final orbit and then flown as a formation during science operations, with a focal length of order 35 m. The DSC is designed to support the payload units (including the provision of the required cryogenic chain) and track the focus point of the mirror as to maintain it at the instrument focal plane.

The MSC design is based on a fixed optical bench, using the volume offered by the LV fairing, a solution that offers a more mass effective structure, simpler baffling and a more favourable thermal environment for the telescope optics, with an effective area exceeding 5 m^2 at 1 keV.

The reference payload is based on a set of core instruments and a set of high priority augmentation units (to be included if resource allows). The core instruments are represented by a single cryogenic Narrow Field Imager (NFI, providing high energy resolution spectroscopy capability between 0.2 and 6 keV over a FOV of 0.75 x 0.75 $arcmin^2$) and a Wide Field Imager (WFI, providing imaging and spectroscopy between 0.5 and 15 keV over a FOV of 7 arcmin diameter). The high priority augmentation units include a second NFI unit, a Hard X-ray Camera (HXC), a High Time Resolution Spectrometer (HTRS) and an X-ray Polarimeter (XPOL).

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2. SCIENCE REQUIREMENTS

The large throughput and good angular resolution of XRO will allow the *detailed* spectral investigation of sources which are too faint for study with the current generation (*Chandra, Suzaku* and XMM-*Newton*) of X-ray observatories. One of the main science goals of XEUS/XRO is to investigate the high-redshift Universe. A large fraction of the total baryonic matter in the Universe is now known to reside in the X-ray emitting component of clusters and groups of galaxies The study of their properties will be another important topic for XRO. The accretion power onto massive black holes is the dominant component of the total X-ray emission in the Universe, so conversely the ability to trace this evolution will be an important diagnostic of the evolution of black holes and the coeval growth of galaxies with cosmic time. Probing the high-energy emitting regions around collapsed objects provides the best laboratory for testing the physics of matter in extreme gravity environments. In addition to these specific themes, the unprecedented high collecting area will make an enormous impact on studies of nearby objects which have been a mainstay of traditional X-ray astronomy, and therefore we also discuss the detailed spectroscopic, timing and polarimetric investigations of brighter objects that will be addressed by XRO. For each of the 3 topics identified in CV2015-2025 call for themes a number of sub-topics have been determined, each of which provides the driver for one, or more, of the science requirements to be met by XRO:

1. Evolution of Large Scale Structure and Nucleosynthesis:
   I. Formation, dynamical and chemical evolution of groups and clusters. This is the driver for spectral grasp, the product of the FOV, area, and spectral resolution for the high spectral resolution instruments.
   II. Baryonic composition of the Intergalactic Medium. This drives the ultimate spectral response required from the high spectral resolution instruments.
   III. Enrichment dynamics, inflows, outflows and mergers. This drives the stability of the absolute spectral calibration of the high spectral resolution instruments.

2. Coeval Growth of Galaxies and Supermassive Black Holes:
   I. Birth and growth of supermassive black holes which drives the overall FOV size and the limiting sensitivity
   II. Supermassive black hole induced galaxy evolution which drives the angular resolution requirements.

3. Matter under Extreme Conditions:
   I. Gravity in the strong field limit with drives the ultimate timing resolution required.
   II. Equations of State studies which drive the product of collecting area and spectral response for the high spectral resolution instruments, as well as the polarization performance.
   III. Acceleration phenomena which drive the high energy (>10 keV) spectral grasp.

Table 1 below provides a summary of the main science requirements [3].

XEUS Science Requirements	
Parameter	**Value**
Telescope Effective Area [m^2]	1.0 at 0.2 keV 5.0 at 1 keV 2.0 at 7 keV 1.0 at 10 keV (goal) 0.1 at 15 & 40 keV (goal)
Angular resolution [arcsec, HEW]	5 2 (goal)
Instrument FOV [arcmin]	7 (WFI) 0.75 (NFI)
Spectral resolution [eV, FWHM]	2 at < 2 keV 6 at 6 keV 1000 at 40 keV (goal)

3. MISSION REQUIREMENTS

The main mission requirements are summarised below. The complete set of requirements to be applied to future system level studies is in preparation.

- Baselined launch vehicle is an Ariane 5 - ECA.
- Direct transfer into halo orbit, with duration of ~ 3 month.
- Halo orbit around L2 (typical amplitude ~ 700000 km, typical period ~ 6 month).
- Autonomous formation flying capability as required by the telescope optical design requirements and as to allow un-interrupted science observations (up to 800 ksec).
- A fixed optical bench.
- Core payload including one Narrow Field Instrument and the Wide Field Imager. High priority augmentation units (second Narrow Field Instrument, HXC, HTRS, and XPOL) to be accommodated as system resource allows.
- Provision of cryogenic chain required to support the science payload.

- Use of functional elements from other ESA missions and introduction of design-to-cost measures as to reduce cost in order to meet the potential CaC allocation.

4. REFERENCE INSTRUMENT PAYLOAD

The actual scientific payload for the X-Ray Observatory mission will be selected on a competitive basis, following an Announcement of Opportunity that will be open to the international scientific community. In order to proceed with the assessment study at system level in an effective manner, it was decided to establish a Payload Working Group with membership from the science community, whose task was to provide detailed input on the design and resource requirements of representative (and state-of-the-art) instruments for the so-called reference payload. The reference payload comprises instruments that satisfy the measurement requirements as defined in [3].
A summary of the XRO reference payload is provided in table 2 below (assuming a focal length of 35m).

Instrument	Parameter	Value
Wide Field Imager (WFI)	Mass (kg):	71
	Power (W):	202
	Operating T:	210 K (detector)
	E range:	0.05-15 keV
	FOV:	7 arcmin
Narrow Field Imager 1 – (NFI1)	Mass (kg):	76
	Power (W):	91
	Operating T:	0.3 K (detector)
	E range:	0.2-6 keV
	FOV:	0.75 arcmin
Narrow Field Imager 2 – (NFI2)	Mass (kg):	43
	Power (W):	115
	Operating T:	0.05 K (detector)
	E range:	0.2 – 6 keV
	FOV:	0.75 arcmin
Hard X-Ray Camera (HXC)	Mass (kg):	45
	Power (W):	33
	Operating T:	220 K (detector)
	E range:	15 – 40 keV
	FOV:	5 arcmin
High Time Resolution Spectrometer (HTRS)	Mass (kg):	16
	Power (W):	84
	Operating T:	250 K (detector)
	E range:	0.5 – 10 keV
	FOV:	1.2 arcmin
X-Ray Polarimeter (XPOL)	Mass (kg):	24
	Power (W):	58
	Operating T:	290 K
	E range:	1 – 10 keV
	FOV:	1.5 arcmin

Two categories are identified: a) core units (WFI + 1 NFI); b) high priority units (2nd NFI, HXC, WFC, XPOL). Presently two different Narrow Field Instrument designs are available:

1) NFI1 is based on a focal plane of Super conducting Tunnel Junctions (STJ), operated at a temperature of < 300 mK via a 3He Sorption Cooler.
2) NFI2 is based on a focal plane array of micro-calorimeters, operated at 50 mK via an ADR.

In consideration of the expected launcher performance and of the resource demands of both Detector Spacecraft and Mirror Spacecraft, it has been assumed to limit the model payload to the Wide Field Camera and a single Narrow Field Imager. Given the early definition stage of the mission, it is not possible to make a definitive choice on the actual NFI design and therefore both designs will be analysed in the context of the XRO/XEUS payload accommodation study. In other words, both configurations (WFI + NFI1 and WFI + NFI2) will be investigated, including different cryogenic chain designs.

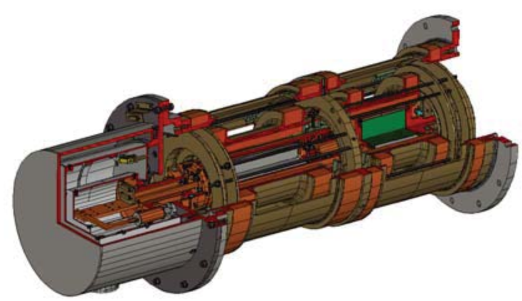

Fig. 1: Adiabatic Demagnetization Refrigerator under development for XEUS (courtesy of *MSSL*).

On the basis of preliminary estimates, it is expected that the nominal XRO payload (WFI+NFI) will have a total mass of order 350 kg (including cryogenic chain) and a power of order 800-900 W.
The science data rate for the nominal payload (NFI+WFI) is presently estimated to be of order 1.0 Mbps. A significant data rate increase is anticipated when considering the presently envisaged needs of some of the high priority payload units (HXC, HTRS and XPOL).

5. THE XEUS MIRROR TECHNOLOGY

The baseline optical design of the XEUS telescope is based on X-Ray High precision Pore Optics (X-HPO),

a technology currently under development with ESA funding [4, 5], in view of achieving large effective areas with low mass, reduce telescope length, high stiffness, and a monolithic structure, favoured to handle the thermal environment and simplify the alignment process. In addition, due to the higher packing density and the associated shorter mirrors required, the conical approximation to the Wolter-I geometry becomes possible. The X-HPO units are fabricated starting from high quality selected 12" (300mm) Si wafers, double sided polished with a flatness better than 180nm (measured over 25x25mm^2). Processed silicon wafer components are then stacked onto a precision Si mandrel, requiring only a single curvature (for the conic surface). Several plates are stacked on top of each other while being curved in the azimuthal direction to form a single monolithic unit that is intrinsically very stiff, as well as possessing very good temperature stability without differential expansion problems.
Two such HPO units, each consisting of 70 ribbed silicon plates, are first co-aligned and then joined together by two CeSiC brackets to form an X-ray Optical Unit (XOU). The XOU provides a three-point interface to the petal structure (figure 2). Precision alignment of the two HPO units is required, forming the conical approximations of the parabola and hyperbola of a Wolter-I optics. The XOU units are small enough (typical size without baffling is 10 cm x 10 cm x 20 cm) to allow simple handling, but large enough to simplify the petal integration.

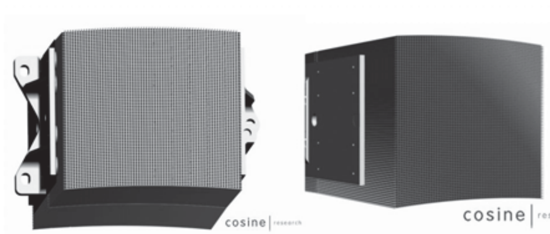

Fig. 2: X-ray Optical Unit (HPO tandem assembly, courtesy of *Cosine Research*).

The XOU's are hard locked into the petals on ground and are not changed / adjusted in flight. The petals also incorporate the baffling systems required, both for X-ray and IR/visible/UV. These baffling systems define the bore sight and field of view of the XRO telescope, and provide in addition thermal and contamination control for the sensitive optics. The petals are mounted on the MSC optical bench and the design of the corresponding interfaces (based on a 3 point, isostatic approach) is ongoing. A petal technology demonstrator is presently under development (ESA contract awarded to Kayser-Threde, Cosine Research, SRON, MPE), with the aim to fabricate a first radially shaped segment, with an external radius of 2100 mm, a depth of ~0.8 m and an angular aperture of about 21 deg (see figure 3).
The HPO development has an angular resolution requirement of 5 arcsec and a goal of 2 arcsec (HEW). Preliminary tests have been conducted on different HPO development models and the first results are now available.

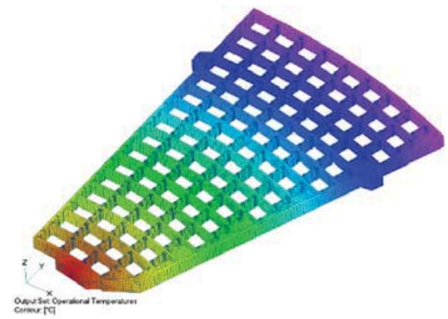

Figure 3: X-HPO petal structure – FEA model (courtesy of *Kayser-Threde*).

6. XEUS TELESCOPE EFFECTIVE AREA

The requirement on the telescope effective area as a function of the photon energy is a major constraint in the design of the mission as it impacts not only on science but also very significantly on the overall system in terms of total S/C mass, formation flying requirements, baffling design and configuration. Although iterations are to be expected as the project evolves, a preliminary analysis has been conducted.
The definition exercise depends on many parameters, such as: mirror size and available geometric area, HPO performance, choice of specific optics coating, focal length. A large number of iterations are required in order to establish the optimal compromise in terms of science performance and available system resource.
The analysis performed to date by ESA in collaboration with members of the Telescope Working Group is based on the assumption of a nominal focal length of 35 m and a geometric area available to the mirror limited by the launcher fairing and by the inner S/C body. The ongoing analysis includes the expected petal and XOU area efficiencies, assuming both the performance of the present optics demonstrator as well as future possible optimisation.
Different assumptions have been made on the adoption of possible single layer coatings on the X-HPO units, such as bare Silicon, uniform Iridium, Gold and Nickel coatings (see figure 4). The additional deposition of

multi-layers (e.g. Carbon over-coating) could allow further performance optimisation, although specific technology development is required [5].
Achieving the requirement of an effective area of 5 m^2 at 1 keV [3] is a high priority for the XRO study that will require specific attention and will be verified in parallel with the evolution of the system configuration and of the optics technology.

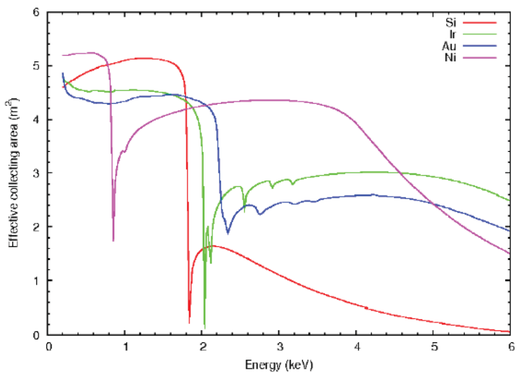

Figure 4: Preliminary estimates of effective area versus photon energy for different X-HPO coatings (without multi-layer coatings).

7. SPACECRAFT CONFIGURATION

The overall S/C configuration will be defined following dedicated industrial activities. Nevertheless, in order to focus the design effort and adequately prepare the industrial work, a preliminary reference configuration has been defined in ESA. Such a configuration is based on the need for Formation Flying (FF), imposed by the telescope focal length (~ 35m). XRO is based on a Detector S/C (DSC) supporting all focal plane instruments, providing the main TM downlink capability to ground control and responsible for maintaining formation with the Mirror S/C (MSC, supporting the telescope mirror). The two S/C units would be launched in a stack (present baseline assumes DSC supported by MSC) and fly to L2 as a single composite (thus reducing operations complexity during transfer and injection) before operating in formation flying mode (see figure 5).
The presently envisaged telescope configuration is based on a fixed optical bench and aims to maximize the available mirror area. The configuration is based on the use of the 1194H adapter and a correspondingly wide inner cylinder, hosting all required subsystems. The radial mirror elements (present assumption is 16 petals, see figure 6) are supported by structural beams, departing from the centre of the cylindrical MSC body. The optics elements are protected from direct Sun illumination by a baffle which also plays an important role with respect to diffuse x-ray straylight rejection and telescope thermal control. The configuration aims to take maximum advantage of the available launcher fairing volume, to meet the requirement of an effective area of 5 m^2 at 1 keV. A distributed (MSC and DSC) approach is adopted for the rejection of the diffuse X-ray background, including a fixed skirt and the Sun baffle on the MSC side and specific baffles for each focal plane instrument on the DSC side.

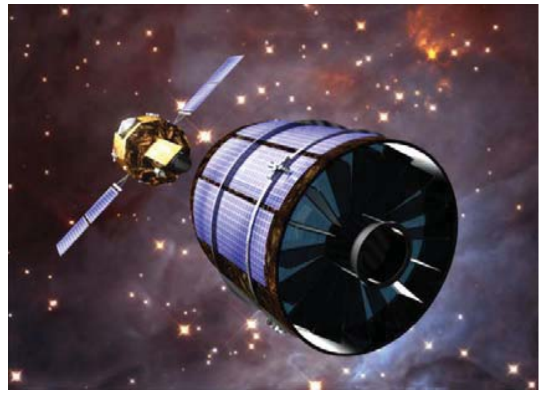

Fig. 5: Artist view of the Detector and Mirror Spacecraft flying in formation at L2.

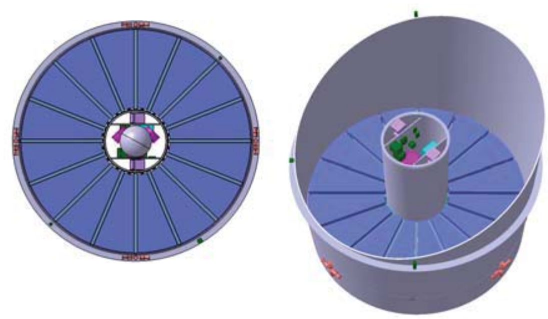

Fig. 6: On-axis and 3D view of the preliminary Mirror Spacecraft (MSC) configuration.

An industrial XRO telescope accommodation study will be placed by the Agency by Q2/Q3 2006. The study will last for 9 month and allow defining the telescope design, including mirror optical bench, thermal control, baffling and interfaces requirements.
The configuration of the DSC is driven mainly by the instrument accommodation requirements (including the corresponding cryogenic chain), by the need for instrument baffling at different focal plane positions. The platform design drivers include the accommodation of the formation flying metrology,

overall thermal control and related interfaces to the cryogenic chain and the payload power and telemetry demands. No specific design activities have been performed on the DSC to date, given the ongoing industrial study on the reference payload accommodation. The overall DSC configuration is expected to be dominated by the choice of the cryogenic chain design.

8. TECHNOLOGY DEVELOPMENTS

A number of technology development activities applicable to the XEUS mission have been promoted by ESA since a few years. The main activities include the development of advanced cryogenic detectors (such as Transition Edge Sensors and Superconducting Tunnel Junctions), cryogenic coolers (such as the Adiabatic Demagnetization Refrigerator) and innovative, low mass X-ray optics (High precision Pore Optics). Activities are well under way, with breadboards and/or engineering models becoming available and being subject of dedicated test campaigns.
More recently ESA has promoted industrial studies addressing specific critical areas, such as formation flying, payload accommodation (Detector Spacecraft) and telescope accommodation (Mirror Spacecraft).
It is expected that the results obtained from such preparatory activities will open the way to future system level studies on solid basis, thus allowing to achieve a high level of definition and to reduce the overall project development risks.

9. PROGRAMMATIC CONSIDERATIONS

Presently XRO/XEUS is a collaboration between ESA and JAXA however the international scenario could evolve as other partners may be sought. Although several preparatory industrial activities, including technology developments as well as S/C definition activities, were planned before the definition of the Cosmic Vision planning and are regularly continuing, no system level industrial study is foreseen until the outcome of the Cosmic Vision mission selection process is clear. Such a mission selection process will also lead to the definition of a realistic project schedule.
Concerning the development schedule applicable to the mirror elements, the breadboard of the HPO module will be delivered to ESA by the end of 2006, while, should the mission proceed further, then an engineering model could be available by 2009, followed by the development of the required production facilities by 2011 and the delivery of the FM units by 2015.

10. CONCLUSIONS

The XRO mission scenario has been recently revisited in order to reduce overall complexity, risk and cost without compromising in a major way the original science return. The revised science requirements are still very competitive with respect to any other envisaged X-Ray mission and ensure a quantum leap in capability compared to XMM-Newton.
A number of preparatory activities have been started at ESA with the goal of consolidating the mission profile before entering into future system level activities to be conducted by industry. Such activities include industrial studies and are focused on the most critical aspects, such as mirror design and related spacecraft configuration, instruments accommodation and related cryogenic chain.
In parallel the technology development activities of XRO/XEUS continue to proceed, with the first test results becoming available from the mirror module breadboard, the cryogenic chain (ADR system) and focal plane detectors (both STJ and TES based).

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