The evolving universe spectroscopy mission (XEUS)

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ABSTRACT

The X-ray Evolving Universe Spectroscopy mission (XEUS) is a potential follow-on to ESA's Cornerstone XMM-Newton. XEUS is designed to become a permanent space-based X-ray observatory covering the waveband from 0.5 to 200 Å with a sensitivity comparable to the most advanced planned future observatories at longer wavelengths, such as NGST, ALMA and FIRST.

Considering the long lead-time of astrophysics missions, ESA started studying XEUS a few years ago and designed a mission scenario, which is able to deliver the performance required by astrophysics at the end of the first decade of the 21st century and beyond.

XEUS will make use of, and rely on, the space infrastructure provided by the International Space Station (ISS) to provide a 10m diameter X-ray optics which will give an effective area of 30 m² at 1 keV. The mirror technology is building on the sophisticated X-ray mirrors developed for XMM-Newton and will give XEUS the necessary angular resolution of 2-5 arcseconds to resolve the extremely large number of sources expected at the very faint levels accessible to XEUS.

XEUS is currently being studied by ESA in cooperation with ISAS/Japan, but the XEUS scenario has a large potential for becoming a 'global' mission with international collaboration on a significant level.

1. THE EVOLVING UNIVERSE

The astrophysics of the 21st century will largely concentrate on the study of the high-redshift universe. Correspondingly the sources to be studied are very distant and faint, requiring very much higher sensitivities than available with today's X-ray observatories¹.

XEUS will be around 250 times more sensitive than XMM-Newton, with a better angular resolution, and its scientific goals will include the study of the:

- First massive black holes,
- First galaxy groups and their evolution into the massive clusters observed today,
- Evolution of heavy element abundances,
- Intergalactic medium using absorption line spectroscopy.

ESA's Plank mission will measure the cosmological parameters to high precision while NGST, FIRST and ALMA will probe the time when the first stars emerged and provide information about the formation and evolution of galaxies. These missions will make observations in the visible and infrared bands and will thus be sensitive in detecting and measuring rather "cool" matter. A powerful X-ray mission such as XEUS² will provide the additional observations necessary to study the hot universe at high-redshift with comparable sensitivity as these

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other facilities. X-ray observations can provide information about the creation of the first black holes and study the strong gravitational field in the immediate vicinity of these objects. X-rays can pierce through the gas and dust in the centers of young galaxies to explore the contributions of accretion and star formation to the history of the early universe (figure 1). Dark matter can be studied through the evolution of large-scale structures traced by the hot X-ray emitting gas trapped in the dark matter potential. Current models predict that the first black holes formed at redshifts of between 10 to 20 with masses of between 100,000 and 10 million solar masses. These are expected to have X-ray fluxes between $2.5 \cdot 10^{-18}$ and $1.0 \cdot 10^{-17}$ erg/cm²/s. The goal for the XEUS sensitivity is to be able to detect these low-luminosity black holes and take detailed spectra of the high-luminosity ones. This will allow the physical and chemical properties of the accreting material to be studied as well as the black hole mass and possibly spin rate.

Figure 1: The evolving universe theme.

By making full use of the facilities available at the ISS in the next century and by ensuring in the XEUS design a significant potential for growth and evolution, the overall mission lifetime of XEUS could be well over a quarter of a century. The power of this observatory will be such that for the first time detailed imaging spectroscopy studies will be undertaken in high energy astrophysics of objects associated with the evolution of the early universe.

2. XEUS: A 10-METER CLASS TELESCOPE IN SPACE

In order to be able to measure the spectra of cosmic sources at redshifts of more than 4, the sensitivity of XEUS must be 10^{-18} erg/cm²/s. Such a sensitivity is obtained by providing a large collecting area of 30 m² at 1 keV. This again implies an optic having a diameter of 10m with a focal length of ~50 m is required to satisfy the scientific requirements of XEUS. Such a large diameter requires a modular design, which is compatible with assembly in space using the infrastructure available at the ISS.

The number of sources increases dramatically in such deep observations, and the images of the sources start to overlap each other on the detectors if the angular resolution of the optics is not better than 5 arcseconds. To achieve an angular resolution of 2-5 arcseconds, the X-ray mirror technology has to be improved by a factor of about 2-5 over the existing XMM-Newton optics. The surface smoothness requirements for XEUS and XMM-Newton on the other hand are very similar, and consequently the mandrel production development is focusing on polishing of improved figures while maintaining the surface finish.

Due to the redshift of very distant objects the interesting characteristic lines (e.g. of iron, which are located around 7 keV) become shifted towards lower energies. Therefore the energy band of greatest interest for XEUS is at rather low energies: the largest effective area of the XEUS optics must be between 50 and 2000 eV.

Since X-rays optics rely on total reflection at shallow incidence angles (of less than one degree), a large focal length is required if the optics diameter is large. For XEUS a focal length of 50m is needed to achieve the desired spectral response with 30 m² effective collecting area in the main observation band up to 2 keV, while still providing more than 3 m² up to 8 keV.

The spectral resolution of the detectors on XEUS must provide sufficient capability so as to separate the spectroscopic lines and thereby establish the physical characteristics of the hot X-ray emitting plasma. Note due to the redshift the X-ray spectra are compressed and even higher spectral resolution is needed than is the case for the current generation of X-ray observatories, which essentially study the more local universe, c.f. figure 2. At 1 keV the spectral resolution required for the XEUS detailed spectral studies must be 2 eV or better.

Figure 2: The simulated response of one of the XEUS cryogenic instruments (NFI) to the Fe-L complex of lines around 1 keV from a hot optically thin plasma at a temperature of 10^7 K, for the case when the redshift changes from (a) $Z=0$ to (b) $Z=3$. The response of a conventional semiconductor based detector (also incorporated on XEUS for wide field studies, WFI) is also shown for comparison. Clearly by a redshift of 3 no line complexes are resolvable over this energy range from a 10^7 K plasma with the WFI.

The basic design goals for the XEUS Observatory are summarized below in Table I.

Table I: The Basic XEUS Design Goals

Parameter	Specification
Energy range	0.05-30 [0.1-100] keV
Telescope focal length	50 m
Mirror Collecting Area @ 1 keV	30 (6) m ²
Mirror Collecting Area @ 8 keV	3 (3) m ²
Spatial resolution	5 arcsec, goal 2 arcsec
Field of View	5 arcmin, goal 10 arcmin
NFI energy Resolution @ 1 keV	2 eV, goal <1 eV
WFI energy resolution @ 1 keV	40 eV
Mission lifetime	>25 years
Orbit	Low earth orbit

NFI = Narrow field imaging spectrometer, WFI = Wide field imaging spectrometer, data ([] refer to a wider energy range under consideration, data () refer to the initial “zero growth” configuration prior to the docking at the ISS.

3. THE XEUS X-RAY MIRROR TECHNOLOGY

The key characteristic of XEUS is the large X-ray mirror aperture combined with good angular resolution and wide-band energy response. This very demanding optics will capitalize on the successful XMM mirror technology and the industrial foundations, which have been already laid in Europe for this program. This XMM mirror technology has placed European science at the forefront in high-energy astrophysics. Unlike XMM however, where a heavily nested mirror was fabricated from closed shells, the XEUS mirror aperture of 10 m diameter is divided into annuli, with each annulus sub divided into sectors. The basic mirror unit therefore consists of a set of heavily stacked thin mirror plates (and not closed shells), each retaining the correct Wolter I geometry. This unit is known as a mirror petal and is a complete free standing calibrated part of the overall XEUS mirror. A schematic of a XEUS mirror petal is shown in figure 3(a). The individual petals are mounted on an optical bench, which forms the main structure of the mirror spacecraft (MSC), as shown in figure 3(b).

Figure 3: (a) A schematic of XEUS Petals, (b) petals forming the XEUS X-ray telescope optics (MSC1).

Currently the XEUS mirror plate production and support are being studied both in terms of finite element analysis and hardware experiments and tests. Simulations have shown that full size mirror plates can be made sufficiently light while maintaining the necessary figure accuracy, if gravity effects are properly considered during manufacture, integration and handling on ground. The hardware tests are currently being carried out on two parallel tracks: (1) production of a 1:3 scaled model petal of X-ray quality, and (2) production of a full-size XEUS structural petal with representative mechanical properties and a surface finish, which is sufficient for optical metrology, see figure 4.

(a)

Figure 4: (a) X-ray quality Wolter I XEUS mirror plates for scaled model petal and (b) full-size structural model XEUS mirror plates.

(b)

4. THE XEUS MISSION PROFILE

The concept of XEUS envisages two separate spacecraft to accommodate the focal length of 50m, the mirror spacecraft (MSC) and the detector spacecraft (DSC). Both are launched together and are self-deployed in an ISS fellow traveler low earth orbit, higher but compatible with the ISS orbit in terms of orbit transfer and ISS visits. The first observation phase of XEUS is started as soon as the two spacecraft are commissioned in orbit, and is expected to last for about 4 years (XEUS1). At that stage XEUS will already have an effective mirror area of 6m^2 at 1 keV and 3m^2 at 8keV, an order of magnitude more than XMM-Newton. MSC1 is moving in an inertial orbit and is pointed to the observation target on the sky with an accuracy of a few $10''$, which is a fraction of the useful field of view of the telescope. DSC1 will track the focal point of the optics and will therefore travel on a forced, non-keplerian orbit. An efficient AOCS sub-system based on solar-electric propulsion (SEP) using hall-effect thrusters and dual-junction GaAs solar arrays is therefore one of the most important new spacecraft technologies employed on XEUS. The DSC1 will measure its position relative to the MSC1 and the focal point by an optical metrology system, and will keep the pointing of XEUS to within $1''$ of the target.

During this first observation phase the preparations on ground for the major growth of the XEUS mirror will continue, and the necessary mirror petals will be finalized and readied for launch, integrated in 8 sectors of 12 petals each. The 8 sectors can be accommodated in a single Space Shuttle (STS) or into alternative ISS transport vehicle(s), to be launched to the ISS.

After closing the first observation period of XEUS, the last major task of the DSC1 is to dock to the MSC1, lower it's orbit using the efficient SEP system, and approach the ISS. The coupled DSC1/MSC1 pair is able to wait in the vicinity of the ISS, outside the safety perimeter, for a period of up to one year, until the ISS is ready to accept the visit of the MSC1. Prior to the actual ISS visit, MSC1 de-docks from the DSC1 and performs the final approach and docking to the ISS under it's own power. The DSC1 is no longer required and is de-orbited. The current baseline XEUS mission scenario is summarized in figure 5.

Figure 5: The XEUS mission scenario.

5. MIRROR ASSEMBLY IN SPACE

Utilizing the extensive infrastructure available at the ISS, the 8 mirror segments are integrated onto the MSC1 to become MSC2, providing XEUS with a 10m diameter X-ray optics. The assembly of MSC2 relies mainly on robotic activity, with support by extravehicular activity (EVA), when and where necessary. Figure 6 shows XEUS1 approaching the ISS (a), and the European Robotic Arm preparing to remove one mirror sector from the carrier structure, which is being held by the main ISS robot arm (SSRMS). ERA then moves each sector to the MSC1, where appropriate mechanisms are activated and latched. The MSC1 rotates around it's axis of symmetry to facilitate the integration. After all 8 sectors are attached to the MSC, the thermal baffles (entrance and exit side of optics), are deployed. EVA is used to complete the assembly, close the thermal blankets and perform the final checks. The mirror petals of the MSC are individually aligned in orbit (FTO) using a dedicated optical laser system and direct observation of well established astronomical calibration fields.

(a)

(b)

Figure 6: (a) The DSC1-MSC1 pair just after separation in the vicinity of the ISS. (b) SSRMS presents the mirror sector transport carrier to ERA for installation on the MSC1.

In the current baseline scenario it is envisaged MSC1 will dock at the ISS using the same docking port as an ATV on the Russian Segment Service Module (RS-SM).

Temporary storage of the transport carrier with the mirror sectors might be required at ISS, in which case the main truss Z1 storage location could be used, if certain operation limitations could be considered. The TC and the mirror sectors will be equipped with the necessary ISS robot arm and STS robot arm grapple fixtures. The mirror sectors will be replaceable into the transport carrier in case of contingencies or emergencies. Other transport facilities to the ISS than the STS also need further examination.

Once the MSC2 is completed and checked-out, it separates from the ISS. The transport of MSC2 to FTO can be done either using the AOCS of DSC2 or by a dedicated booster motor on MSC2. Correspondingly, DSC2 is launched either into the ISS orbit or directly into FTO. This needs to be further studied with respect to ISS logistics, fuel consumption and DSC2/MSC2 detailed design.

6. THE XEUS X-RAY TELESCOPE

The MSC will operate as a spinning spacecraft rotating about its major axis at ~ 1 degree/second so as to ensure the thermal requirements of the X-ray mirror can be met, essentially distributing the heat uniformly over the circumference of the spacecraft. The pointing direction of the MSC1 will be restricted due to stray light, thermal and power requirements.

The angle between the telescope pointing and the sun-vector will always be in the range $90 - 120^\circ$ during the observation phase of the mission. Slews between individual XEUS fields will be short ($\leq 10^\circ$) and will be executed during the daylight part of the orbit. Any re-pointing of XEUS will require a coordinated sequence of activities involving the MSC and the DSC attitudes and the DSC position relative to the MSC.

The effective area of the XEUS X-ray mirrors is shown in figure 7.

Figure 7: Effective area of XEUS X-ray mirror. ‘-1’ refers to XEUS as initially deployed, ‘-2’ refers to XEUS after the mirror growth at the ISS.

The model payload of DSC1 includes three X-ray imaging spectrometers (WFI, NFI1 and NFI2), with the main characteristics described in table II.

Table II: The DSC1 Model Payload Characteristics

Characteristic	WFI	NFI1/2
Detector type	CCD	TES & STJ
Operating Temp.	200-260 K	15-300 mK
Cooling	Radiator	Stirling cooler +ADR/ ³ He
Detector Size	70x70 mm ²	7x7 mm ²
Pixel size	40 μ m	100 μ m
Time Resolution	5 μ s (1 ms)	1-5 μ s
Energy range	0.1-30 keV	0.05-3 (NFI1) 0.5-10 (NFI2)
Mass (total)	60 kg	350 kg
Power (total)	60 W	300 W

Note that the WFI can be cooled passively using a multiple stage radiator on the anti-sun side of DSC1. The effective environmental heat sink temperature in the XEUS orbit will not be lower than 190 K for some selected DSC1 locations avoiding the sun exposure. For the two narrow field imaging spectrometers, flat panel radiators with heat pipes will dissipate the thermal energy from the closed cycle mechanical coolers, which are used as the main cooling stage to a base temperature of 2 K. The cooling to 300 mK or 15 mK will be achieved using a closed cycle ³He sorption pump or an ADR respectively.

The first observation period can be regarded as the initial mission to study the universe from $Z=1\sim4$ prior to that of the fully grown XEUS, which may reach redshifts as high as $Z\sim10$ ($\sim3\%$ of the universe current age). The replacement of

DSC1 by DSC2 after about 4 years will implicitly be a replacement of the detector instruments of XEUS with updated, more evolved systems. When XEUS then returns to the FTO with its fully expanded 10m mirror, XEUS is sufficiently sensitive to explore the early evolving universe at X-ray energies to a level comparable to the observations at longer wavelengths and lower photon energies performed by NGST, FIRST or ALMA.

CONCLUSIONS

The XEUS mission represents an ambitious project full of new approaches and technologies and with very demanding science goals. XEUS utilizes the available space infrastructure at the ISS and provides a world class observatory to observe the hot evolving universe with unprecedented sensitivity, complementing the sensitive observations of the cooler universe to be expected from other future missions currently under study.

The baseline strategy of XEUS allows it to take advantage of the key attributes of the ISS as an in-orbit assembly facility, while minimizing the complexity of the tasks and resource demands required of the ISS. The large X-ray mirror implies a serious mass, even if very advanced technologies are employed, due to the required high angular resolution and hence mechanical stability of the X-ray mirror surfaces. The low earth orbit (LEO), necessitated for ISS-compatibility reasons, seems to be the only economically justifiable option, if uplift costs are considered. The growth of the X-ray mirror at the ISS provides a significant increase in the effective area at the most relevant energies for studying the high redshift universe (~ 1 keV). This growth capability is crucial for achieving the ultimate scientific aims of the mission.

The replacement of the DSC in LEO every 4-5 years requires a small to mid-size launcher or a shared launch, and extends the operational lifetime of XEUS to about a quarter of a century, since only marginal degradation of the optics is expected in orbit. The detector instruments are kept at the cutting edge of technology, with a very convenient replacement period compatible with typical evolution time-scales for such instrumentation.

The service of the MSC at the ISS after 4-5 years and the easy replacement of the DSC in LEO in case of failures of critical spacecraft systems increase substantially the reliability of XEUS as a whole. Note that the MSC is kept as simple as possible (albeit heavy), and most active and therefore more failure-prone systems are located on the DSC, including the X-ray detector instruments. Future access to the MSC2, either for refurbishment or replenishment of consumables, can be either performed directly by the Space Shuttle or possibly through a re-docking to ISS or berthing near to the ISS.

The XEUS scenario offers also programmatic advantages, since the production of the mirror is spread over a period of more than 10 years. This allows better optimization of the industrial production of the large number of mirror plates required to achieve such a large effective area. At the same time a continual improvement in the mirror petal technology with time is possible. For the production of the DSCs advantages are also evident, since the busses will be rather similar with a production rate of about one per 5 years. Future DSCs after DSC2 are envisaged, but these can, like DSC2, be launched directly into FTO, with new instruments and consumables.

An industrial feasibility study concluded positively the evaluation of the novel XEUS scenario, and technology development programs have advanced the mirror technology remarkably. Further detailed system level studies are now required, focused as follows.

At payload level the most demanding issues seriously needing attention over the next few years are:

- The development and demonstration of the 2 - 5 arc second performance of the basic mirror petal unit
- The development of efficient low temperature imaging spectrometers providing a resolution below 1 eV and < 5 eV at 1 and 8 keV respectively.
- The development of a large format high- speed wide field imaging solid state spectrometer.
- The development of the low temperature closed cycle cooling system.

At the spacecraft and mission level a number of technical and logistical issues need to be addressed:

- The DSC orbit control system and the optimization of the propulsion system.
- The DSC-MSC metrology and alignment system
- Compatibility with ISS (docking, robotics)
- The rendezvous and docking of MSC to the ISS
- Straylight protection (optical and X-ray)
- Stability of optical benches, petal alignment system
- Thermal stabilization and control

Key issues regarding the ISS activities, which need more detailed studies and confirmations, are:

- The logistics and costs involved in the transport of mirror sectors to the ISS by STS or alternative transport
- The external storage locations and capability at the ISS.
- New ERA base-point at the RS-SM is required, together with minor modification of the end-effector of ERA.
- Docking of MSC1 to the ISS and de-docking of MSC2 from the ISS.
- Possibility of berthing XEUS (MSC2 and/or DSC2) near to the ISS for repairs or consumable replenishment.

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