The XEUS mission and Instruments

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ABSTRACT

The X-ray Evolving Universe Spectroscopy mission (XEUS) is an ambitious project under study by the European Space Agency (ESA), which aims to probe the distant hot universe with comparable sensitivity to NGST and ALMA. The effective optical area and angular resolution required to perform this task is 30 m^2 effective area and $<5''$ angular resolution respectively at 1 keV. The single Wolter-I X-ray telescope having these characteristics will be equipped with large area semiconductor detectors and high-resolution cryogenic imaging spectrometers with 2 eV resolution at 1 keV. A novel approach to mission design has been developed, placing the detector instruments on one dedicated spacecraft and the optics on another. The International Space station (ISS) with the best ever-available infrastructure in space will be used to expand the mirror diameter from 4.5 m to 10 m, by using the European Robotic Arm on the ISS.

The detector spacecraft (DSC) uses solar-electric propulsion to maintain its position while flying in formation with the mirror spacecraft. The detector instruments are protected from straylight and contamination by sophisticated baffles and filters, and employing the Earth as a shield to make the most sensitive low energy X-ray observations of the heavily red-shifted universe. After completion of an initial observation phase lasting 5 years, the mirror spacecraft will be upgraded (basically expanded to a full 10 m diameter mirror) at the ISS, while the DSC is replaced by a new spacecraft with a new suite of detector instruments optimised to the full area XEUS mirror.

An industrial feasibility study was successfully completed and identified no major problem areas. Current activities focus on a full system level study and the necessary technology developments. XEUS is likely to become a truly global mission, involving many of the partners that have teamed up to build the ISS. Japan is already a major partner in the study of XEUS, with ISAS having its main interest in the first DSC.

Keywords: X-ray astronomy, Space observatory, X-ray instrumentation, ISS utilisation, international collaboration

1. THE XEUS SCIENCE CASE

The starting point for the development of XEUS [1,2,3,4] was the assessment of the astrophysics science requirements in the post- XMM-Newton/Chandra era, with consideration of the facilities in other wavebands planned for that timeframe. The study of the organisation of hot matter in the early universe, with the formation of the first black holes and clusters of galaxies, and their evolution emerged as the most important observations to be made by XEUS. The measurements of the properties of objects at a time the Universe was just a few percent of its current age require the acquisition of X-ray spectra at fluxes of $<10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$. Such sensitivity requires a large effective area for the optics, which in turn requires a large focal length if a prohibitive number of focal plane instruments is to be avoided. As indicated in figure 1, the sensitivities of NGST in the IR, First in the far-IR, ALMA in the mm and the VLT in the visible range are comparable to that of XEUS. To avoid source confusion at such deep observations, the angular resolution of the telescope must be between 2 and 5 arcseconds. Due to the very large distance of the objects, the spectra are highly redshifted, with z between 5 and 10, and therefore the main energy band for XEUS is 50 to 2000 eV.

Figure 1: Comparison of the sensitivities of future observatories in different wavebands. A horizontal line corresponds to equal power output per decade of frequency. Assumptions: ALMA: 50 antennas of 10m diameter, 8h integration, FIRST: 5 σ detection with 1 h exposure for photometry and spectroscopy respectively, NGST: 5 σ detection in 10ksec for photometry, VLT: 5 σ imaging, XEUS: 100ksec exposure. The solid and dashed lines show the spectral energy distribution of a hypothetical 3C273-type quasar at redshifts of 10 and 20, respectively.

2. MISSION DESIGN AND STATUS

The science requirements have the largest implication on the optics design. The combination of large effective area (>20 m² below 2 keV) and good angular resolution (requirement of 5'' with a goal of 2'') result in a large diameter telescope (10 m diameter) having very good figure and stiffness and associated large mass. In order to implement such a large X-ray telescope in space, a new mission design and scenario had to be developed. The concept is illustrated in figure 2 and discussed below.

X-ray optics have a long lifetime in space, but are heavy and require a large effort to be launched into space. Due to the large size required to fulfil the XEUS science requirements, current state-of-the-art X-ray mirror technologies require a build-up in space. Both factors lead to the choice of a low Earth orbit, which at the same time provides a low detector background and allows the use of the Earth as a sun-shield for a large fraction of the orbit.

The X-ray optic, with a diameter of 10 m, will be composed of modular elements called petals, which are individually produced, tested and calibrated, and later aligned to each other in-orbit. The XEUS mirror is initially launched with a diameter of 4 m, and is later extended to a 10 m diameter in orbit. By choosing a low Earth orbit sufficient mass can be allocated to the mirror so as to achieve the required angular resolution, assuming a single Ariane 5 launch for the first phase, and a Shuttle for the mirror expansion elements. The concept of the mirror extension in orbit at the ISS is supported by an industrial feasibility study successfully conducted by the ESA Manned Space Flight Directorate in conjunction with the Space Science Directorate.

In order to fulfil the energy bandwidth requirement, a focal length of 50 m is required. Since such large structures become unpractically complex and heavy, a more elegant solution was found in formation flying the detectors and the optics on two separate spacecraft. The larger Mirror Spacecraft (MSC) keeps an inertial keplerian orbit, with the Detector Spacecraft (DSC) following the focus of the X-ray telescope.

Detector instruments in general evolve at a faster pace than X-ray optics (which is analogous to the HST in the visible regime, which keeps the optics, but changes and upgrades the detector instruments). By placing the instruments on the separate DSC, the detectors can be simply replaced as desired by replacing the complete DSC (note that the DSC forms only 35% of the initial launch mass of XEUS). The investment made into the production and launch of the optics is maintained and remains functional for the following DSCs. Current analysis show that a lifetime of 4 to 5 years may be expected for each detector spacecraft. But the lifetime of the expanded mirror spacecraft could be up to 25 years.

Figure 2: The XEUS concept starts with the science requirements and considers: (1) the large mass of high resolution large area X-ray optics, (2) the more rapid evolution of X-ray detectors (compared to the optics) and the desire for a regular exchange, (3) the existence of available infrastructure in space (the ISS) for the optics extension, and (4) the long focal length required (50 m), which is provided by the separate detector and mirror spacecraft.

Having a single focal plane on XEUS is a real asset, considering the cost of instruments and signal/noise considerations. A replacement of instruments at regular intervals will provide the possibility to keep the instrumentation up to date and flexible, supporting long-term detector instrument technology development activities, as the science objectives are modified due to the expansion of the discovery space.

An industrial system level study of XEUS will shortly be starting, again involving not only the science directorate of ESA, but also its manned spaceflight directorate and the Japanese space science agency ISAS. Technology studies are under way or in preparation, focusing on the XEUS optics, the detector instruments and generic technologies, e.g. cooling and formation flying. A demonstration of formation flying will occur in 2007 with the ESA SMART2 technology demonstration mission.

XEUS is an exiting global mission, open to further international collaboration. The mission consists of clearly defined and separate building blocks with clean interfaces (MSC1, MSC2, DSC1, DSC2, ISS operations, MSC1/DSC1 launch, MSC2 uplink, DSC2 launch, operations). Continuous instrument development is supported by the mission concept, with regular replacements of the DSC, while maintaining the long term investment in the optics.

3. OBSERVATION EFFICIENCY

XEUS is launched into a fellow traveller orbit (FTO) to the ISS, in order to make a single visit to the ISS possible. The orbit altitude is optimised with respect to radiation background and orbit stability, and is baselined at 600 km. As indicated in figure 3, the apparent earth radius from such an orbit is 66° . Assuming an earth avoidance angle of 4° , a double cone of 40° diameter on each side of the orbit is available for the pointing of XEUS, providing continuous coverage of the target. Due to the inclination of the XEUS orbit of 51.6° , and the inclination of the ecliptic, practically the complete sky (98%) can be covered with continuous visibility of the target, by appropriately scheduling of the observations throughout a 2 year period. At any time a target of opportunity may be observed outside these cones, although the observation efficiency will not be 100% any more.

Figure 3: The XEUS orbit is a fellow traveller orbit to the ISS, with a higher altitude optimized for radiation background and orbit stability. Targets on the sky can be continuously observed within two cones of 40° diameter.

Further pointing constraints are given by the relative position of the Sun, Moon, Earth, and possibly bright planets, as well as spacecraft constraints, mainly for thermal and propulsion efficiency reasons. In figure 4 an example for the momentary sky map is shown, indicating the individual constraints and the observable sky area. This sky map changes with the progress of the spacecraft in its orbit, the precession of the orbit and the revolution of the earth. The map evolves slowly enough to allow targets to be observed continuously for a few days, if required. In the figure it is also shown, that at the selected time XEUS is outside the South Atlantic Anomaly (SAA) and in Earth shadow. During passages through the SAA the

instruments might remain operational, although the background will increase. When in the shadow of the Earth the observations at the lowest available X-ray energies will be made . When in sunlight, filters will be changed and the lowest observable X-ray energy will rise from 50 eV to a few 100 eV (the cut-off energy will be strongly dependent on the filter technology).

Figure 4: Example for the momentary sky map for XEUS, showing the pointing constraints. In the brightest areas on the map, all constraints are fulfilled. Over the XEUS orbit, the precession period of the XEUS orbit (79.7 d) and the revolution of the earth, the pattern evolves, with the integrated continuously observable sky area covering the complete celestial sphere within one year. The pattern changes slowly enough to allow uninterrupted observations of a given target for a few days. At the indicated time XEUS is not in SAA and in the shadow of the Earth.

Over the course of the year the area of best observation efficiency drifts across the sky, covering the major fraction of the celestial sphere within one year. In figure 5 the integrated observation efficiency is shown as a function of sky coordinates for the period of one year. Note that over a period of 2 years, the bright areas, representing 100% observation efficiency and uninterrupted observations, extend over all the right ascension range. Limited periods of time exist, when uninterrupted observations are not possible due to inconvenient combinations of the observation constraints. During those times the observation efficiency can drop to a low of 60%, and those time intervals will be used to slew the spacecraft for re-pointing. The average time in SAA (with increased background in the detector instruments) is about 7%, while the average time in Earth shadow is about 30%.

Re-pointing of the XEUS spacecraft was studied in a feasibility study successfully completed in industry. A 10° slew can be accomplished within 20 minutes. The procedure involves the required attitude change for both DSC and MSC (individually, with reference to the sky using star-trackers), and the repositioning of the DSC. This repositioning of the DSC occurs automatically, with the DSC simply continuing to follow the focal point of the MSC optics, as during nominal observation periods. Effectively the positioning system is used as in the observation mode, and the re-positioning is regarded as a standard correction manoeuvre.

Figure 5: XEUS sky visibility map, integrated over one year. Within the bright areas, any target can be observed continuously for typical durations of a few days, assuming proper scheduling. Over about two years the white areas cover all Right Ascension angles. Also indicated are the fractions of the time spent in SAA and in sunlight. Note the lowest observation efficiencies are about 60%, with the residual fractions used for manoeuvring the spacecraft for re-pointing.

4. WIDE FIELD SPECTROMETER

The X-ray detector instruments are the payload of the DSC, which will be tracking the focus of the X-ray telescope (MSC) to within ± 1 mm. This implies that the DSC1 will be flying in a non-Keplerian orbit, at a distance of 50 m from the MSC. Solar-electric propulsion will be used to achieve a suitable lifetime of the orbit control system, well in-line with the detector instrument lifetime. The XEUS design specification, including the detectors, is given in table I.

Table I: The Basic XEUS Design Goals

Parameter	Specification XEUS (XEUS1)
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

The semiconductor based Wide Field Imager (WFI) will be used to acquire deep images with a spectroscopic resolution of 40 eV at 1 keV over large fields of 10 arcmin diameter. The WFI can, particularly if implemented as a DEPFET pixel array, be cooled passively using a multiple stage radiator on the anti-sun side of DSC. The effective environmental heat sink temperature in the XEUS orbit will not be lower than 190 K for some selected DSC locations avoiding the sun exposure. Non-destructive read-out schemes with very low noise offer a clear advantage, improving energy resolution and allowing higher operation temperatures.

Being at the focal plane of a 50 m focal length telescope, the WFI will have to cover a physical area of 150 mm diameter. The plate scale is 242 micron per arcsecond, and therefore the detector pixel size may be rather large, of the order of 100 micron, despite the good angular resolution of the telescope optics.

A possible observation strategy for XEUS will involve a first image of a rather large field and with a large depth, followed thereafter by the selection of targets for high spectral resolution observations with the same or better sensitivity. Essentially very reddened objects, which are indicators of a large redshift, will in general be the targets for high resolution studies.

The large effective area of the telescope (30 m^2 at 1 keV) will require innovative read-out schemes, particularly for the WFI. A random-access detector like the DEPFET permits the use of different read-out frequencies for different areas (fast readout in regions of high brightness (relatively speaking) while low read-out frequencies are sufficient for the major part of the detector area, which is mostly background or distant faint sources). Such a flexible readout architecture will also provide very fast readout speeds for selected areas of the array, up to possibly 50 kHz. Such a capability will enable timing studies to be performed with very high sensitivity and time resolution. Each photon would be time-tagged to a precision of better than 1 millisecond, possibly 20 microseconds.

5. HIGH RESOLUTION SPECTROMETERS

The detailed study of selected sources in a rather small field of view (goals of covering 30 to 60 arcseconds) will require cryogenic detector instruments to achieve the sensitivity required by the XEUS science case. The large bandpass of XEUS suggests the use of two different types of such spectrometers, optimised for lower and medium energies, respectively. Figure 6 presents the energy resolution requirements as a function of X-ray energy for different physical parameters to be measured. In addition, the performance achievable with Transition Edge Sensors (TES) and Superconducting Tunneling Junctions (STJ) is also plotted. Both technologies complement nicely each other, with a crossover point at about 3 keV (depending on the details of the implementation of the detectors). Two narrow field high-resolution cryogenic imaging spectrometers are therefore foreseen as the baseline payload for XEUS, NFI1 and NFI2, complementing the WFI.

For the cooling of the two NFI, flat panel radiators with heat pipes will dissipate the thermal energy from the closed-cycle mechanical coolers that 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 adiabatic demagnetisation refrigerator (ADR) respectively. The ADR cooling is being studied by ESA as a generic technology required for XEUS.

The spectral resolution goal is 1 eV at 1 keV (with a requirement of 2 eV) and 5 eV at 8 keV. Combined with the large effective area of the telescope optics and the associated sensitivity, detailed spectroscopic studies will be possible to a very large depth.

A high countrate capability is desired (although the large focal length and correspondingly large plate scale permits many pixels to read out each angular resolution element). Timing studies will be possible to large distances. Time tagging to a few microsecond is foreseen, providing a high timing accuracy at high sensitivity for distant periodic sources. The STJ in particular is expected to provide in addition a very high count rate capability, of a few kHz per pixel.

The required physical size of the cryogenic instruments is challenging, considering the operating temperatures and the IR protection, but realistic, requiring a diameter of 7 mm (for 30 arcsecond fields) to 15 mm (corresponding to one arcminute field of view).

The high resolution spectrometers will further be very useful for performing absorption line spectroscopy with rich detail and high sensitivity, for large scale structure measurements.

Figure 6: Resolving power as function of X-ray energy necessary apply different diagnostic techniques to X-ray spectra. Also plotted are the resolving powers obtainable with typical STJ and TES based detector systems. The combination of both systems provides the best coverage of phenomena, with the crossover point located at about 3 keV.

6. HIGH ENERGY RESPONSE OPTION

The large focal length of XEUS allows for the possibility to expand the energy response towards the 50 to 100 keV area. This extension is not regarded as a main driver for XEUS, but would add to the science return.

A possible implementation with little impact on core mission science and mission design consists of coating the inner 8 petals with multilayers (super-mirrors) and adding a high energy detector behind the WFI. In practice the later would be accomplished by placing a GaAs- or CZT-based detector a few centimeters behind the WFI main detector. Both detectors would operate at the same temperature and would share the structure and cooling system. The focal depth of the 50 meter focal length XEUS telescope is sufficient to provide a resolution of 4 arcseconds for the high energy detector, if placed 25 mm behind the nominal focal plane of the telescope. Note that only the inner petals, i.e. up to a radius of 2 meters, would be used for the high energies, with a correspondingly small opening angle. The required change to the inner petals is only the application of the multilayer coating onto the mirror plates prior to the integration into the petal structure. The effect of the super-mirror coating onto the angular resolution of the mirrors has to be investigated further, before a decision on the use of this option can be taken.

In figure 7 the effective area of the XEUS telescope is given for the current baseline (all mirrors gold coated) and for the option with the inner ring of 8 petals having super-mirror finish. Should it be possible to produce multilayer mirrors which would not degrade the angular resolution of the optics (a requirement), the high energy instrument (integrated into the WFI) would provide a similar resolution as the provided for the main bandpass of XEUS at lower energies. Significant effective area could be provided up to 40 or 50 keV, depending strongly on the detailed design of the multilayer structure.

Figure 7: Effective area as a function of X-ray energy for XEUS with and without the application of multilayer coatings to the inner 8 petals. For comparison also the effective areas of some other current and future missions are given.

7. CONCLUSION

The definition and optimisation of the mission design and scenario is proceeding well. Many ideas were generated and are being explored with regard to a further optimisation of the mission.

A system level study will be started shortly, detailing the mission design and studying in more detail specific technical areas. In parallel accompanying technology studies concentrating on the optics technologies, detectors and generic technologies such as the cooling are occurring and expanding in scope.

The existing space infrastructure will be utilised to build a sufficiently large and long duration X-ray astrophysics facility, maintaining the investment in the optics, which has a long lifetime in orbit. Regular replacement of the detector spacecraft ensures the availability of state-of-the art instrumentation at any time.

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