The X-ray Evolving Universe Spectroscopy Mission (XEUS)

M. Bavdaz[1], J.A.M. Bleeker[2], G. Hasinger[3], H. Inoue[4], G. Palumbo[5], A. Peacock[1], A. Parmar[1], M.J. Turner[6], J. Truemper[7], J. Schiemann[8]

[1]*Space Science Department of ESA, ESTEC, Noordwijk, The Netherlands*
[1]*Space Research Organization Utrecht (SRON), The Netherlands*
[3]*Astrophysikalisches Institut Potsdam, Germany*
[4]*Institute of Space and Astronautical Science (ISAS), Japan*
[5]*Dipartmento dipartimento di Astronomia, Universita degli Studi di Bologna, Italy*
[6]*Department of Physics and Astronomy, Leicester University, United Kingdom*
[7]*Max Planck Institut für Physik und Astrophysik, Garching, Germany*
[8]*Directorate of Manned Spaceflight and Microgravity ESA, ESTEC, Noordwijk, The Netherlands*

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M. Bavdaz[*1], J.A.M. Bleeker[2], G. Hasinger[3], H. Inoue[4], G. Palumbo[5], A.Peacock[1], A. Parmar[1], M.J. Turner[6], J. Truemper[7], J. Schiemann[8]

[1]Space Science Department of ESA, ESTEC, Noordwijk, Netherlands
[2] Space Research Organization Utrecht, Netherlands,
[3] Astrophysikalisches Institut Potsdam, Germany,
[4]Institute of Space and Astronautical Science (ISAS), Japan,
[5]Dipartimento di Astronomia, Universita degli Studi di Bologne, Italy,
[6]Dept. Physics and Astronomy,Leicester University,United Kingdom,
[7]Max Planck Institut Physik und Astrophysik, Garching, Germany,
[8]Directorate Of Manned Spaceflight and Microgravity ESA, ESTEC, Noordwijk, Netherlands

ABSTRACT

XEUS : The X-ray Evolving Universe Spectroscopy mission represents a potential follow-on mission to the ESA XMM cornerstone currently nearing completion. XEUS represents the next logical step forward in X-ray astrophysics after the current set of missions have been launched and completed their operational lives. The development and ultimate success relies heavily on the capability of the International Space Station (ISS). In this paper we describe the key characteristics of the mission including the requirements placed specifically on the ISS and discuss the significant advances in high energy astrophysics expected from such an observatory.

The aim of XEUS is to study the astrophysics of some of the most distant and hence youngest known discrete objects in the universe. The specific scientific issues, which XEUS aims to address, can be summarized as follows:

- To measure the X-ray spectra of objects with a redshift z >4 at flux levels about $<10^{-17}$ erg cm^{-2} s^{-1}. This is at least a 100 times fainter than XMM.
- Where possible to determine from the X-ray spectral lines the redshift and thus the age of these objects
- To thereby establish the evolution in the distribution of matter in the early universe

To achieve these demanding aims a large X-ray telescope is required. The basic features of this telescope are:

- An X-ray mirror with an effective collecting area at 1 keV of 30 m^2.
- A spatial resolution of the mirror needs to be at least 5" (HEW) so as to avoid source confusion at above mentioned faint source levels.
- A field of view of at least 5' is required so as to ensure that a significantly large population of high redshift x-ray sources can be observed in a single pointing.
- Energy bandwith required is 0.05 to 30 keV, with 3m^2 at 8 keV.
- An energy resolution of 1-10 eV is required to perform detailed plasma diagnostics on sources, such as distant galaxy clusters

These are some of the most demanding requirements yet placed on any X-ray astrophysics mission and will require major technological development at all levels – optics, detectors and spacecraft.

Key Words : X-ray Astrophysics, Future missions, Evolving universe

[*] Correspondence: E-mail: mbavdaz@estec.esa.nl; Telephone: +31 71 565 4933; Fax: +31 71 565 4690; ESA/ESTEC, SCI-SA, P.O.Box 299, NL-2200AG Noordwijk, The Netherlands

1. INTRODUCTION

XEUS : The X-ray Evolving Universe Spectroscopy mission is under study as envisaged by the Horizons 2000 Survey Committee, who recommended "analysing the potential offered by a major high energy astrophysics facility within the Space Station (ISS) Utilization Programme". The original mission concept has arisen through extensive discussions by the European Scientific Community, particularly at the Workshop held at Leicester University UK in July 1996. At this international workshop the foundations for the "Next Generation of X-ray Observatories" was laid. With XMM due for launch in early 2000, with a mission duration of 5-10 years, it is not too early to consider the post XMM era. At the turn of the century two great X-ray observatories will have embarked on their astrophysics programs – XMM and NASA's Chandra and thus the requirements of XEUS must take account of the key thrusts and potential discoveries from both these powerful missions.

The XEUS mission aims to do this by placing a permanent X-ray observatory in space, that provides a telescope aperture equivalent to the largest ground based optical telescopes – essentially the equivalent of the VLT for X-ray astronomy in space. 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. THE SCIENTIFIC RATIONALE FOR XEUS

The astrophysics of the 21st century will largely concentrate on the study of the high-redshift universe. This will allow fundamental questions to be addressed,such as:

- How did the first galaxies form?
- What is the history of the large-scale structure visible today?
- How and when were the elements created?
- What were the first discrete objects?
- What is the nature of dark matter?

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. A powerful X-ray mission such as XEUS will provide the additional observations necessary to study the hot universe at high-redshift with comparable sensitivity as these 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. Dark matter can be studied through the evolution of large scale structure 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 e-18 and 1.0 e-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 properties and chemical properties of the accreting material to be studied as well as the black hole mass and possibly spin rate. The potential of these studies is shown in figure 1 where the redshifted iron line profile of a moderate mass black hole at a redshift of 10 is shown. The iron line, which has a rest energy of 6.4 keV is clearly detected at at energy of ~0.6 keV with sufficient statistics to allow its profile to be measured in a 10^6 s deep-field observation.

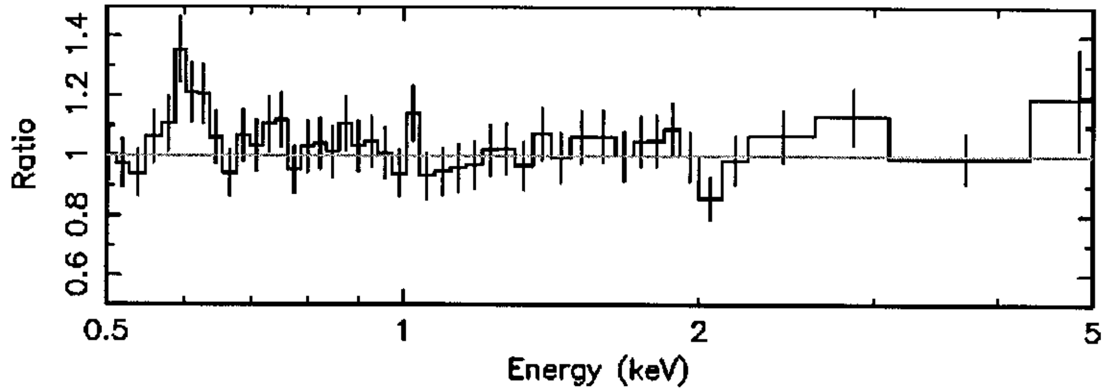

Figure1: The result of simulations of a 350 eV equivalent width (at z=0) double horned Fe line from an AGN at a redshift (z) of 10 with a luminosity of 10^{44} erg s^{-1} (2-10 keV; rest frame). An exposure of 1000 ks using the low energy NFI is assumed together with line of sight absorption equivalent to 10^{21} atoms cm^{-2} and an intrinsic column of 5.10^{21}1atoms cm^{-2}. The Fe line is clearly detected at 0.6 keV and its energy and profile can be measured - the key to doing astrophysics.

3. THE XEUS BASIC DESIGN FEATURES

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	5-10 arcmin
NFI energy Resolution @ 1 keV	1 eV
WFI energy resolution @ 1 keV	40 eV
Mission lifetime	25 years
Orbit	LEO

NFI = Narrow field imaging spectrometer
WFI = Wide field imaging spectrometer
$^{+}$Data ( ) refer to a wider energy range under study
$^{++}$Data ( ) refer to the initial "zero growth" configuration

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, each retaining the correct geometry. This unit is known as a mirror petal and is a complete free standing calibrated part of the overall XEUS mirror with a spatial resolution of ~ 5 arcsecond (goal 2 arcsec) covering a large bandwidth from 0.05 – 30 keV. This is the significant technological evolution, which requires study and which should lead to a dramatic increase in capability over XMM. A schematic of a XEUS mirror petal is shown in Figure 2.

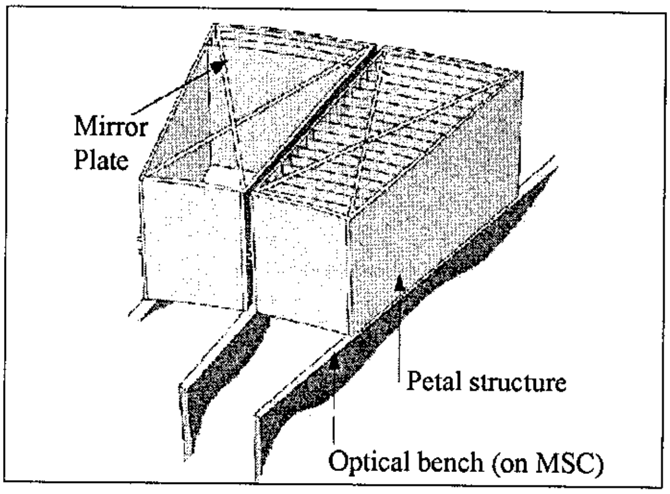

Figure 2 : A schematic of XEUS Petals

The second area of the scientific payload requiring major development will be the narrow field imaging spectrometers, which have an energy resolution of 1 eV at 1 keV as a goal. These instruments will have to be based on very low temperature sensors, possibly transition edge sensors or superconducting tunnel junctions operating at a temperature of 15-300 mK.

The concept of XEUS envisages two separate spacecraft to accommodate the focal length of 50m, the mirror spacecraft (MSC) and the detector spacecraft (DSC).

4. THE MIRROR SPACECRAFT (MSC1)

The payload of MSC1 consists of the large Wolter I mirror, subdivided into mirror petals. These petals are mounted onto a stable and stiff support structure (optical bench) and are individually aligned in orbit using a dedicated optical laser system and direct observation of well established astronomical calibration fields. Each petal consists of ~ 100-200 X-ray reflecting plates made by nickel electroforming on precision mandrels. All plates are integrated into the petal structure and aligned and calibrated on the ground. The petals in the MSC1 (zero growth) cover a circular area with an outer and inner diameter of ~ 4.4 and 1.3 m respectively. The central core is not used for petals. Provisions on the MSC1 support structure will be made to allow for the expansion of the MSC1 into MSC2. This growth provides a significant increase in the effective area at the most relevant energies for studying the high redshift universe (~ 1 keV). The growth is essential to push the spectroscopic limits to the highest redshifts and therefore the youngest objects.

The mirror petals are very sensitive to contamination and temperature variations. Each petal is protected from contamination during launch, maneuvering and docking with the DSC1 and while in the vicinity of the ISS by hermetically sealed doors. The operating temperature of each petal must be maintained constant to ~ 1° C so as to prevent deformations of the highly accurate mirror plates. The expected operating temperature of the XEUS mirror is – 35° C. This places rather important requirements on the petal ground calibration and simulation software. While each petal contains an integrated stray light and thermal baffle as part of the unit, the MSC1 will operate as a spinning spacecraft rotating about its major axis at ~ 1 degree/second so as to ensure the thermal requirements can be met, essentially distributing the heat uniformly around the circumference of the spacecraft. In addition the MSC contains large thermal baffles to shield the mirror from direct sunlight. The design of this baffle is critical, since the thermal loads from the sun will be periodic due to the orbit. Table II summarizes the details relating to the mirror petals and mirror.

The MSC1 bus is located in the central hub of the MSC1. It will be thermally isolated from the mirror optical bench and maintained at a constant 20° C. This bus provides power and telemetry (to ground and DSC1), controls the attitude, thermal environment and docking. The MSC1 telemetry contains only housekeeping data, involving only low data rates.

Table II : Details of the XEUS Mirror

Parameter	Specification
Mirror plate material	Nickel
X-ray reflecting surface	Gold
Plate thickness	300 microns
Plate length and width (typical)	1m x 0.5 m
Number annuli (zero growth)	2
Number of petals (zero growth)	2x 16
Petal Baffles (entry & exit)	2x100 mm
Typical Petal Mass	200 – 350 kg
Mirror mass (zero growth)	8900 kg
Number of annuli added	3
Number of sectors added	8
Number of petals/sector	12
Diameter of full grown mirror	10 m
Mass of mirror fully grown	17400 kg

The MSC will be flying in low earth orbit but will not actively control its orbit during observations. The MSC1 will have a complete attituse and orbit control system, compatible with the requirements for docking to the ISS. Major orbit changes, e.g. for visiting the ISS, will be performed using the DSC1 orbit control system after docking to the DSC1. 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° during the observation phase of the mission. Slews between individual XEUS fields will be short (≤ 10°) 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 MSC1 and the DSC1 attitudes and the DSC1 position relative to the MSC1. Typical expose times per pointing are envisaged to be 10^5 to 10^6 seconds. Note the pointing accuracy of the MSC1 does not need to be particularly high (~ goal of 10") due to the field of view of the XEUS mirror (5-10'). The actual attitude will be measured to a much higher accuracy with a-posteriori reconstruction of ≤ 1". Finally the MSC1 will provide references to the DSC1 to establish the relative position of the two spacecraft via a laser alignment system on the main axis of symmetry.

The docking port is located on the mirror entry plane and supported on a rotating platform, simplifying the robotic addition of mirror sectors at the ISS. Figures 3 and 4 show the MSC1 in side view and cross section.

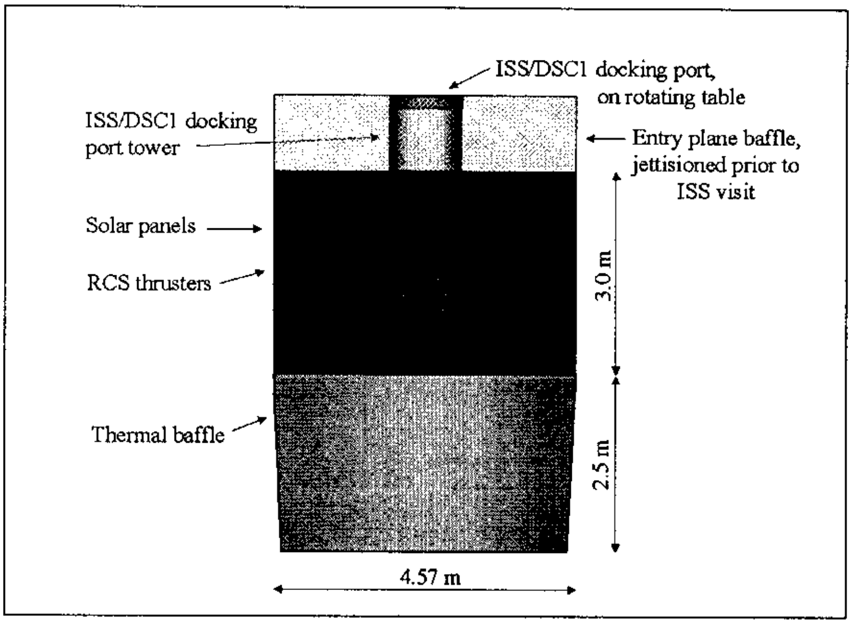

Figure 3: MSC1, side view

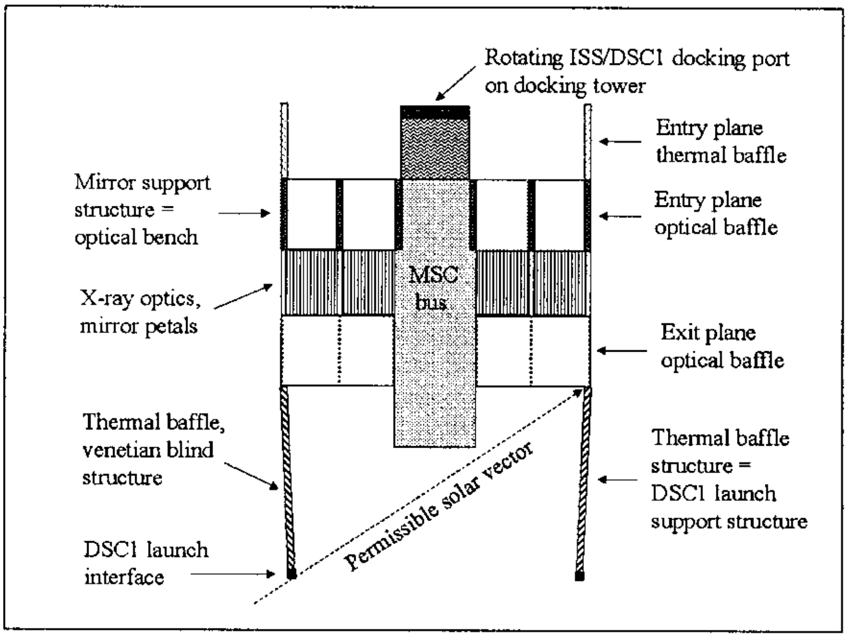

Figure 4: MSC1, cross section

5. THE DETECTOR SPACECRAFT (DSC1)

The X-ray detectors (spectrometers and imager) are the payload of the DSC. The DSC1 will be tracking the focus of the X-ray telescope (MSC1) to within ± 2 mm. This implies that the DSC1 will be flying in a non-Keplerian orbit. The orbital characteristics of this MSC1-DSC1 tandem pair is summarized in Table III.

This table refers to the nominal mission start with XEUS inserted directly into the Fellow Traveler Orbit (FTO). This orbit will naturally decay with a mean and maximum orbit decay rate of –0.55 and –4.7 km/year respectively. The DSC1 will be flying in a similar orbit, but simply shifted by 50 m against the pointing direction of XEUS. The peak forces required to keep the DSC1 on station in this orbit depend on the angle α between the XEUS orbital plane and the XEUS pointing direction. The smallest force is required for the largest α. For $0 < \alpha < 90°$ the average force is 540 - 350 mN requiring a dv of ~ 0.3 – 0.5 m/s per orbit. Thus observations at high declinations will require less propellant and will therefore be preferred in the mission planning. All other forces acting on the DSC1 are about two orders of magnitude lower than the non-Keplerian orbit forces and can be compensated by the DSC1 orbital control system. Table IV summarizes the requirements with respect to the DSC1 orbit control system based on the average of the forces discussed above.

Table III :Orbital Characteristics of the DSC/MSC

Parameter	Specification
Altitude	600 km
Eccentricity	0
Inclination	51.6 deg
Period	97 min
Maximum eclipse	35.5 min
Node spacing	24 deg
Node precession	-4.5 deg/day
De-orbit dv	256 m/s
Altitude change dv	0.54 m/s/km
Plane change dv	132 m/s/deg
Earth angular radius	66 deg
Range to horizon	2831 km

Table IV : Details of the DSC Orbit Control

Parameter	Specification
DSC1 launch mass (kg)	6000
Peak Forces (worst case)	700 mN
Average dv over 1 orbit	0.37 m/s
Average dv over 1 day	5.6 m/s
DSC FTO to ISS dv	111 m/s

Static plasma thrusters (SPT) will provide the force to keep the DSC1 in it's orbit. These thrusters must be distributed such, that the thrust axis distribution is as isotropic as possible in order to minimize thruster power and propellant. This need arises from the orbital inclination and its precession coupled to the different pointing directions required by XEUS., which leads to constantly changing forces around the orbit. Issues related to the lifetime, cycle times and thrust control and dynamic range will be important for the final thruster selection.

The DSC1 dry mass is ~ 3100 kg. About 2900kg of inert Xenon propellant will be loaded into the DSC1 before launch, giving the DSC1 an observation lifetime of about 5 years. The DSC1 will require about 14 kW of power for the worst case eclipse, of which 13 kW are for the electric propulsion system.

Figure 5 shows a perspective view of DSC1 looking at the anti-solar side, which shows the thermal radiators of the instruments. Solar panels are sized for the DSC1 power requirements and are shown in figure 5 positioned for the case when XEUS is pointing at a low declination target, i.e. the array normal is tilted 120° from the XEUS optical axis. Note that the solar array is always kept perpendicular to the sun. The DSC1 is ~ 2.8 m cube with deployable solar arrays that have a full span of 26 m and a width of ~ 7.9 m.

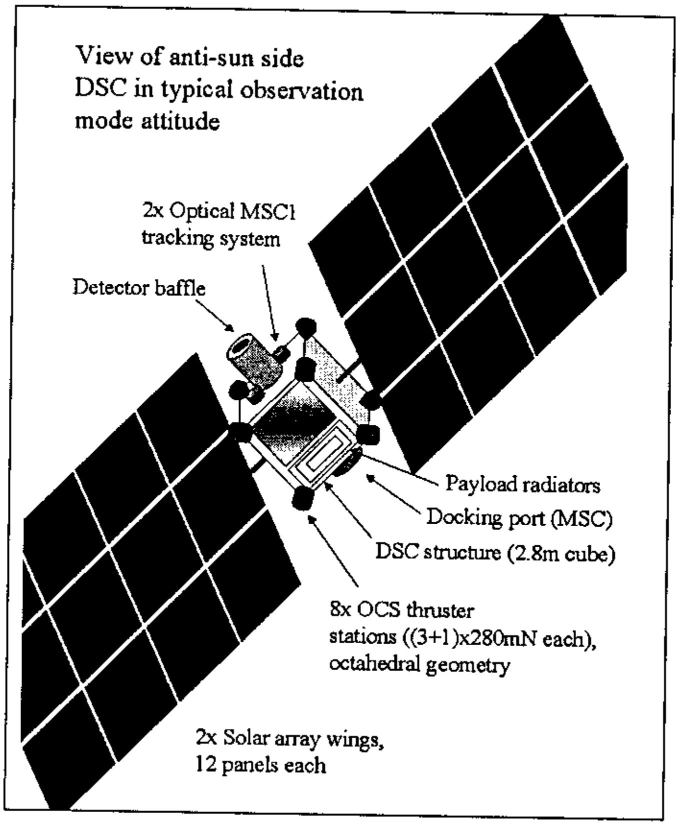

Figure 5: DSC1, perspective view

The payload of DSC1 will include three X-ray imaging spectrometers (WFI, NFI1 and NFI2). Their main characteristics are summarized in Table V. The payload is subject to a on-going detailed study and as such the data in table V should be considered as provisional.

Table V : The DSC1 Payload Characteristics

Characteristic	WFI	NFI1/2
Detector type	CCD	TES & STJ
Operating Temp.	200-260 K	15-300 mK
Cooling	Radiator	Stirling+ADR
Detector Size	70x70 mm^2	7x7 mm^2
Pixel size	40 μm	100 μm
Time Resolution	5 μs (1 ms)	1-5 μs
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 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 ^{3}He sorption pump or an ADR respectively.

6. THE XEUS MISSION PROFILE

The XEUS spacecraft consists of two free flying spacecraft: a detector spacecraft (DSC) and a mirror spacecraft (MSC) separated by ~ 50 m and aligned in the low earth orbit by an active orbital control and alignment system. Such a large aperture mirror cannot be deployed in a single launch. In the current baseline scenario it is envisaged to launch the "zero growth" XEUS mated pair (MSC1+DSC1) directly into a Fellow Traveler Orbit (FTO) to the ISS using an Ariane 5e or similar launcher. The FTO is a low earth orbit, altitude ~ 600 km with an inclination similar to the ISS. The mated pair will decouple in FTO and the DSC1 will take up station 50 m from the MSC1. After alignment validation and normal spacecraft/payload checkout the "zero growth" astrophysics observation program will commence. The MSC will point at a given target field and maintain a stable attitude while the DSC1 will maintain the focal distance and alignment with respect to the MSC1 so that the field image as measured by the DSC1 detectors remains stable.

It must be stressed that XEUS is in this scenario completely autonomous from the ISS. In the initial launch "zero growth" configuration the MSC1 will contain only the two inner annuli of the telescope filled with 32 petals. The XEUS initial collecting area is however huge (~6 m^2 at 1 keV) but still has substantial room for growth through use of the ISS. This growth capability is crucial for achieving the ultimate scientific aims of the mission.

The pair of XEUS spacecraft can however be re-mated in orbit and, through the use of the orbit control system (OCS) on DSC1, allow the mated pair to perform an orbit change and come to the vicinity of the ISS. At this point the pair is able to wait for up to one year by following the ISS in a safe distance, until the later is ready to receive the MSC1 for refurbishment and growth. Prior to the docking to the ISS the DSC1 will separate from the MSC1, and then the MSC1 will approach and dock to the ISS. As far as possible, docking technology developed for the Automated Transfer Vehicle (ATV) will be used. The DSC1, after de-docking from the MSC1 and it's usefulness at an end, will undergo a controlled de-orbit.

It must be stressed, that XEUS will be able to start its astrophysics observing program effectively from day 1 after launch of the "zero growth" configuration into FTO.

7. THE ACTIVITIES AT THE ISS

In the current baseline scenario it is envisaged that the mated XEUS pair (MSC1 +DSC1) will arrive in the vicinity of the station from FTO and the MSC1 will then dock at the ISS using the same docking port as an ATV on the Russian segment. This rendezvous with the ISS, which will take advantage of the evolution of the XEUS orbit with respect to the ISS, will occur on a timescale of ~ 4-5 years. At the ISS the MSC1 is grown to MSC2.

In preparation for the MSC1 visit to ISS the required 8 mirror sectors, each containing 12 petals, will be brought to the ISS. This may occur close to or at the time of the MSC1 visit. A Space Shuttle could transport the required 8 sectors in one flight (see figure 6). Alternatively a period of up to 5 years is available for individual transport of sectors to the ISS, in which case external storage of the mirror sectors is required. The mirror sector structure serves as the transport container.

The top level activity envisaged at the ISS after the MSC1 has docked with the ISS can be summarized as follows :

- Retrieve the sectors required to expand the mirror from the zero growth ~4.5 m diameter to the final diameter of ~10 m from external storage areas or the transport vehicle.
- Insert the 8 sectors into MSC1 mirror support structure. Note that each mirror sector is ~ 1600 kg (see figure 7)
- Deploy the thermal baffle elements of the MSC2 (figure 8).
- Perform checkout of MSC2.
- De-dock MSC2 and move it to the ISS safety perimeter.
- Transfer MSC2 orbit to FTO.

After MSC2 arrives in FTO, DSC2 is launched into the MSC2 orbit and the fully grown Xeus starts observations.

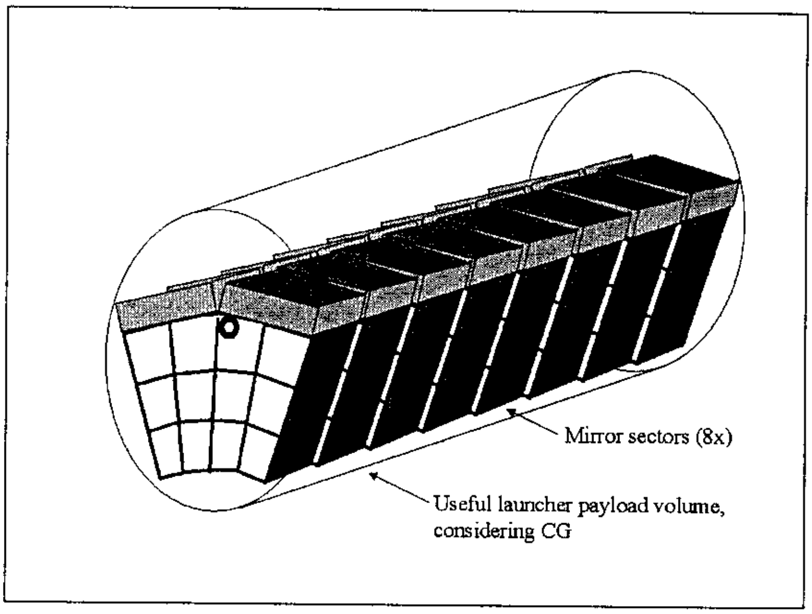

Figure 6: Stowage of mirror sectors and thermal baffle elements (CG: center of gravity)

The mirror growth phase at the ISS may involve the use of robotics such as the European Robotics Arm for handling petals and a limited amount of EVA. The SSRMS might be used to transport the sectors from the storage area or the transport vehicle to the MSC1. The mirror sectors will contain jigs and tool points for robotic manipulation. For cleanliness reasons the mirror sectors are hermetically sealed.

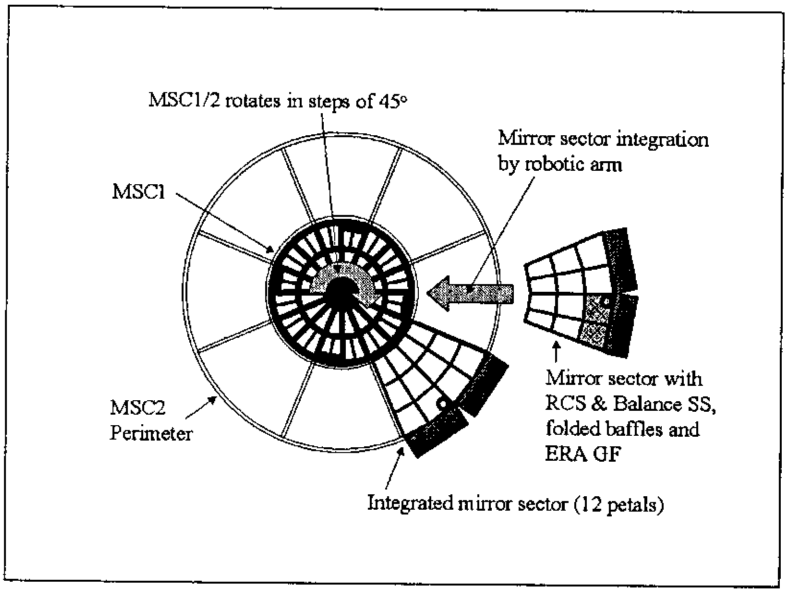

Figure 7: A schematic of the XEUS mirror growth

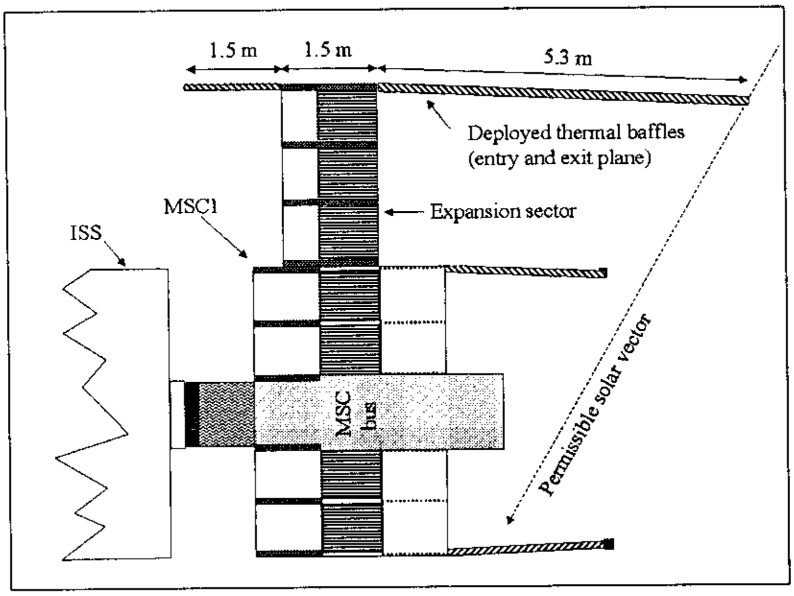

Figure 8: Cross section of MSC docked to the ISS

Key issues regarding the ISS activities, which need addressing, are :

- The logistics and costs involved in the transport and stowage of sectors and baffle elements at the ISS.
- The external storage locations and capability at the ISS.
- Technical issues relating to the transport of sectors at the ISS
- Sector insertion into the MSC1 support structure using 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.

This baseline strategy allows Xeus 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. In addition the delay between the zero growth launch into FTO and the rendezvous with the ISS allows :

- The costs of production of the mirror to be spread over a period of more than 10 years.
- The continual improvement in the mirror petal technology with time.
- The spreading of the launch costs.
- The production of a series of low cost DSC busses spread over 10 years or more. Note that at spacecraft level all busses after DSC1 are identical since the MSC1 has evolved into the final mirror MSC2.
- Development of new improved focal plane instrumentation incorporated into DSC2 and follow on DSCs.

Future DSCs after DSC2 are envisaged, but these can, like DSC2, be launched directly into FTO, with new instruments and consumables. The MSC2 contains a fully expanded mirror system at this stage. 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.

8. CONCLUSIONS

The XEUS mission represents an ambitious project full of new approaches and technologies. 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 < 10 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 as follows :

- The DSC1 orbit control system and the optimization of the propulsion system.
- The DSC1-MSC1 metrology system
- The transport to the ISS and possibly storage of a large amount of cargo externally at the ISS
- The rendezvous and docking of MSC1 to the ISS
- The feasibility of the robotics and EVA activity while MSC1 is docked at the ISS

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The X-ray Evolving Universe Spectroscopy Mission (XEUS) The X-ray mirror design and technology

M. Bavdaz[1], M. Beijersbergen[1], A. Peacock[1], R. Willingale[2], B. Aschenbach[3], H. Brauninger[3]

[1]Space Science Department of ESA, ESTEC, Noordwijk, The Netherlands
[2]Department of Physics and Astronomy, Leicester University, United Kingdom
[3]Max Planck Institut für Physik und Astrophysik, Garching,

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