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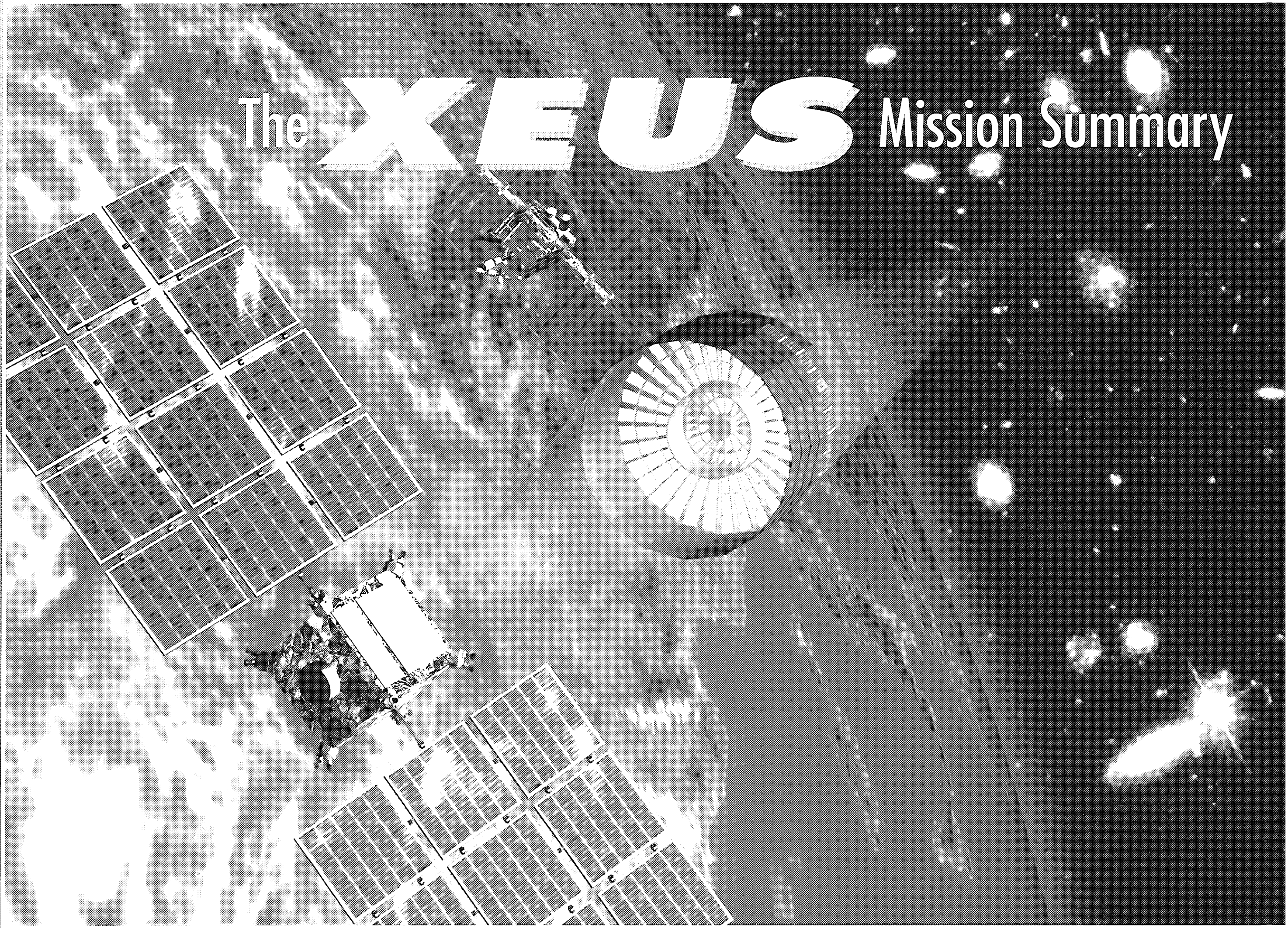
The XEUS Mission Summary



European Space Agency
Agence spatiale européenne

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Prepared by the XEUS Steering Committee:

J.A.M. Bleeker, SRON, The Netherlands
G. Hasinger, AIP Potsdam, Germany
H. Inoue, ISAS, Japan
G. Palumbo, Bologna, Italy
A. Peacock, ESA/ESTEC, The Netherlands
J. Trümper, MPE, Garching, Germany
M. Turner, University of Leicester, United Kingdom

and the XEUS Study Scientist:

M. Bavdaz, ESA/ESTEC, The Netherlands

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X-ray Evolving-Universe Spectroscopy - The XEUS Mission Summary

The X-ray Evolving-Universe Spectroscopy Mission XEUS will trace the evolution and origins of hot matter back to an epoch when the Universe was only a few percent of its current age. XEUS will use the unique spectral signature of an accreting black hole – its gravitationally and Doppler distorted iron line, to establish the redshift and hence the distances and ages of some of the first discrete objects in the Universe. In addition, studies of groups and clusters of galaxies back to their appearance at cosmologically significant redshifts will allow large-scale structure formation and metal synthesis to be addressed. XEUS embodied as the staged and evolutionary development of a large, long-lived, X-ray telescope facility in low Earth orbit, taking maximum advantage of the in-orbit infrastructure provided by the International Space Station, meets these scientific objectives in an optimum and highly cost-effective way. With a lifetime of over a quarter of a century and a capability to regularly replace the instrumentation without the need for any manned space activity, XEUS, a truly global mission, will provide the worldwide astrophysics community with a permanent facility to explore the deepest regions of our evolving Universe.

1 The Key Science Issues

In the first decade of the 21st century new vistas in X-ray astrophysics are emerging, in particular in the area of high-resolution X-ray spectroscopy with the advent of the latest X-ray space observatories, Chandra and XMM-Newton. Given the long lead times of major next generation space astronomy missions, arising from the need for substantial technological advance, now is the time to assess the mainstream prospects for X-ray astrophysics that will remain when these two powerful observatories complete their missions sometime around 2010. The answer is, in a nutshell, relatively straightforward: cosmology and the unique role X-ray observations play in a coherent study of the properties of the evolving Universe.

In the coming decade major progress is expected in the understanding of the evolution of the geometry and density of the very early Universe, assuming a successful completion of the Planck and MAP missions in high-resolution mapping of the temperature fluctuations in the cosmic microwave background.

Following on from this primordial phase, an in-depth and coherent study of the subsequent formation and evolution of structure in the Universe will need a highly sensitive "dual-track" observational approach studying both the properties and evolution of the *cold* baryonic matter and in a highly complementary way the *hot* baryonic matter. This scenario is depicted in Figure 1. Cold Dark Matter (CDM) models for hierarchical structure formation predict that primordial fluctuations in the dark matter density grow and become non-linear. Small structures collapse first with the baryons initially collapsing together with the dark matter. If the baryon clouds cool and lose their kinetic energy, they become self-gravitating. Cool dense phases of the matter trigger the formation of stars or gravitationally bound protostellar systems possibly as early as a redshift, z, of 10-30 and galaxy formation will follow. Almost certainly this will occur beyond z ~ 5 (see Figure 1).

The formation of structure on the stellar/galaxy mass scale will be probed in the infrared and submillimetre domains with, e.g., the NGST, FIRST and ALMA observatories. However, it is becoming increasingly apparent that the first formation of supermassive black holes (M_{BH} 10^5-10^7 $M_\odot$) is an integral feature of the galaxy formation process and therefore that these first black holes should also originate at high redshift, i.e. possibly beyond z = 10 but certainly at z > 5 (Figure 1, red panels). The only way to discover these first holes, which can have X-ray luminosities in the range 10^{43}-10^{44} erg s^{-1}, and to study their growth and evolution with redshift, is through X-ray spectroscopy!

X-ray spectroscopy is also an essential tool by which to address structure formation on much larger mass scales than individual galaxies as is amply evidenced by the scale of hot intracluster gas in rich clusters of galaxies in the local Universe, where the hot gas represents more than twice the baryonic matter content contained in the total of all cluster galaxies. Models for structure formation in the Universe, starting from the seed inhomogeneities, indicate that the major fraction of matter in the present

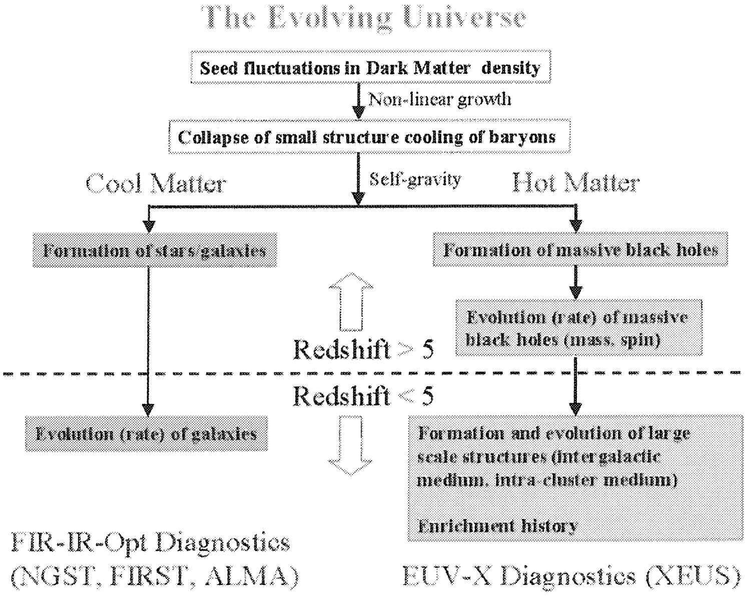


Figure 1a. The cold and hot phases of the evolving Universe

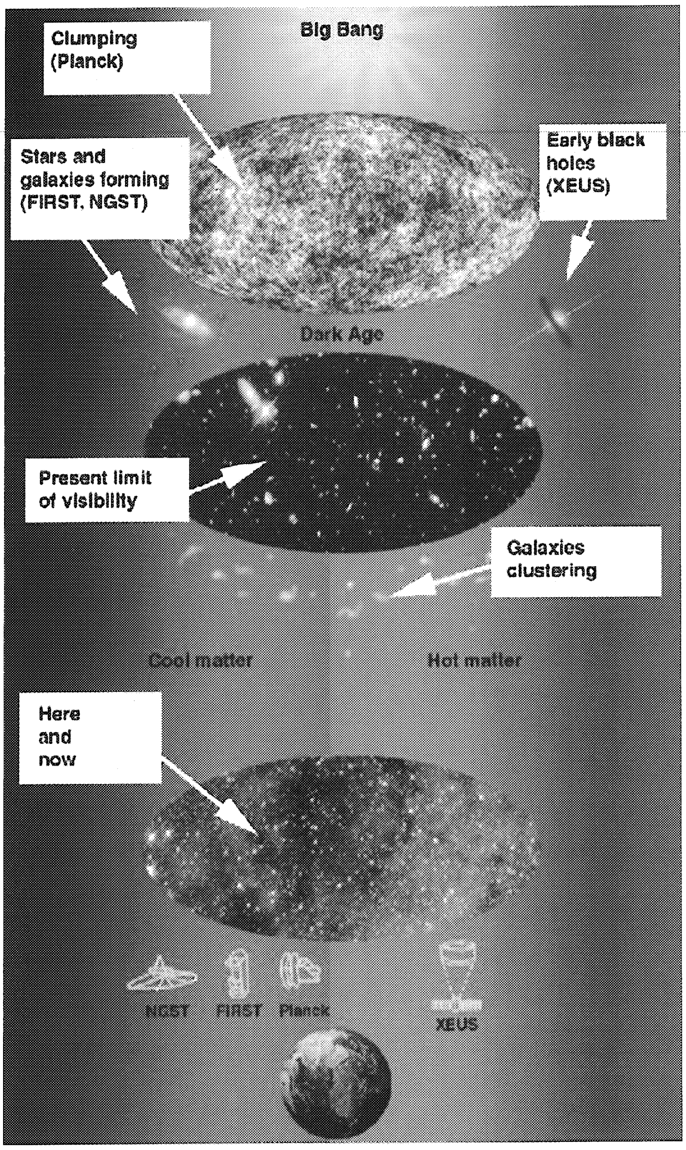


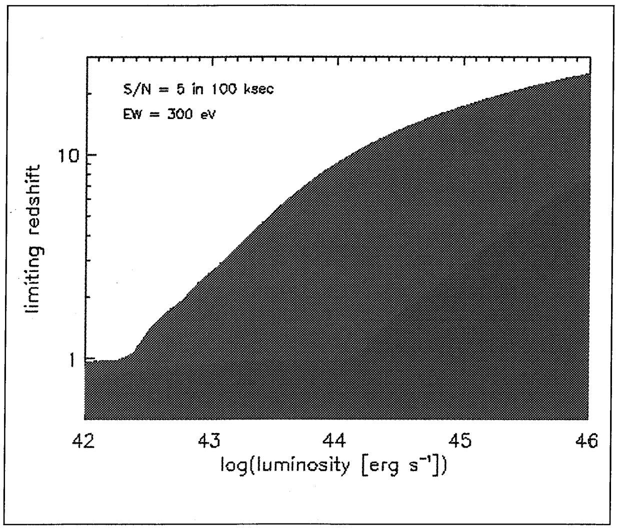
Figure 1b. The overall exploration of the Universe through probing of the hot and cold baryonic matter in discrete structures

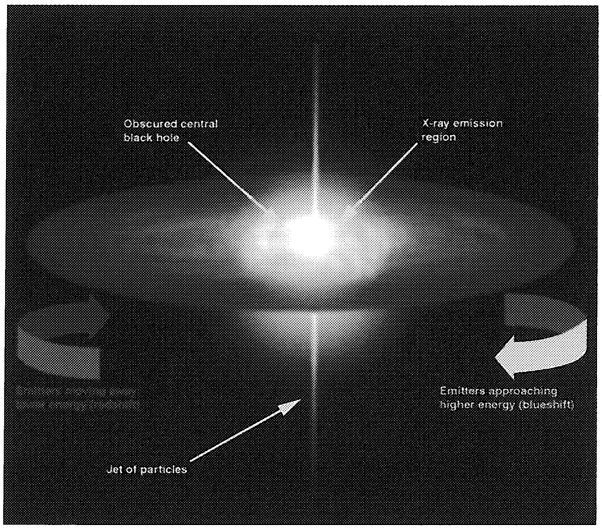
Universe is hot with temperatures in the range 10^5-10^7 K. The luminosity – temperature relation of clusters and groups of galaxies indicates that a significant amount of additional heat may have been injected into the intergalactic medium, making the Universe even hotter. The, potentially dominant, hot matter component evolves simultaneously with the cool matter detected in the infrared and sub-millimetre domains and can only be traced through high-resolution X-ray spectroscopy, both in emission and through absorption features in luminous background sources.

The key scientific goals for any post-Chandra/XMM-Newton major X-ray astrophysics mission can therefore be summarized as:

- Detection of massive black holes in the earliest Active Galactic Nuclei (AGN) and estimates of their mass and spin. Significant constraints on the origin and growth of massive black holes can only be derived if observations probe the population beyond z = 4-5. This imposes an important design constraint on the spectral sensitivity in order to allow the detection of the redshifted relativistically broadened Fe-K emission from very distant sources.

- Study of the formation of the first gravitationally bound, dark-matter-dominated systems, i.e. small groups of galaxies, and tracing of their evolution to the present epoch since they may well constitute the dominant fraction of the current mass density of baryons. This requires at least the ability to measure a prominent X-ray spectral feature of a moderately enriched (0.3 solar) small cluster with a temperature of 10^7 K at $z \sim 2$.
- Study of the evolution of metal synthesis down to the present epoch. Since metallicity is very sensitive to local density contrasts, a large spread in metallicity is to be expected at a particular redshift for individual systems. However, the tenuous hot Intra-Cluster Medium (ICM) is substantially less sensitive to this density contrast and therefore X-ray spectroscopy is a much more robust probe of the chemical evolution of the Universe. Note that absorption line spectroscopy of the Ly-α forest only probes the intrinsically metal-poor low-density phase. To assess the enrichment history properly, statistical variations at a given redshift should be averaged out, i.e. the spectroscopic sensitivity of the telescope





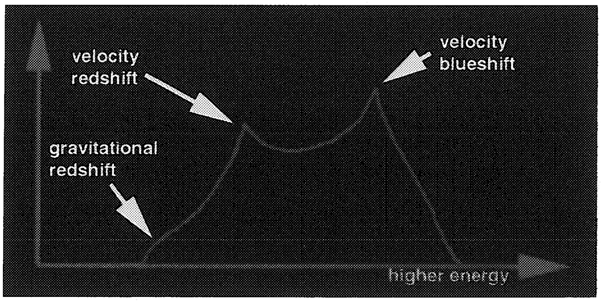


Figure 2. The ability of XEUS2 to detect and measure the properties of massive primeval black holes (left panel). The red region is for XEUS2 while the blue region shows the sensitivity of XMM-Newton. The right-hand panels show schematically the formation and overall shape of the double-horned profile expected from the iron K line emitted from the hot inner regions of the accretion disk

should allow coverage of a large number of target fields on an almost routine basis.

- Characterisation of the true intergalactic medium (IGM), i.e. its mass, density, temperature and metallicity, most likely dominated by a hot (10^5-10^7 K) filamentary structure. Appropriate background sources for absorption spectroscopy are high-redshift luminous quasars and the X-ray afterglows of gamma-ray burst sources.

2 Performance

The above science goals can be met with the following key observatory characteristics:

- A spectroscopic area above 20 m^2 below 2 keV with a spectral resolution below 2 eV, sufficient for a significant detection of the most prominent emission lines, i.e. O VII, Si XIII, and Fe XXV against the sky background.
- An angular resolution of between 2 and 5 arcseconds, sufficient to minimise the effects of both source confusion and the diffuse galactic X-ray background.

While the mission characteristics are outlined in Section 3, it is sufficient to say here that lying at the heart of XEUS is a large, high-resolution, X-ray telescope which will be grown in orbit through a two-stage process (XEUS1 & 2) in partnership with the International Space Station.

2.1 Formation of massive black holes

Figure 2 shows the ability of XEUS2 (fully deployed) to track massive black hole formation in the Universe by measuring the distorted Fe-K emission lines originating in the strong gravity field in the immediate vicinity of the black hole. The limiting redshift is given as a function of the luminosity of the AGN, assuming a 300 eV (rest frame) equivalent width emission line (5σ detection in 100 ks). The shape of the Fe-K line is invariant to the mass of the black hole, but depends on the black hole's spin rate. Thus, studies of the line shape as a function of redshift will allow an investigation of whether black holes grow through continuous accretion, or by the merging of smaller black holes. For distant AGN, where reverberation mapping is not an option, indirect, mostly statistical, methods can be used to estimate the black-hole masses. At sufficiently early times, the time scale for doubling of the mass by Eddington limited accretion corresponds to an ever increasing redshift interval. At a redshift of 4 to 5, within reach of the fully deployed XEUS for luminosities above 3×10^{43} erg s^{-1}, the growth of the massive black holes stretches to very early times and even a statistical mass estimate, or limit, will put significant constraints on the initial mass of the holes, their growth rate and their epoch of formation.

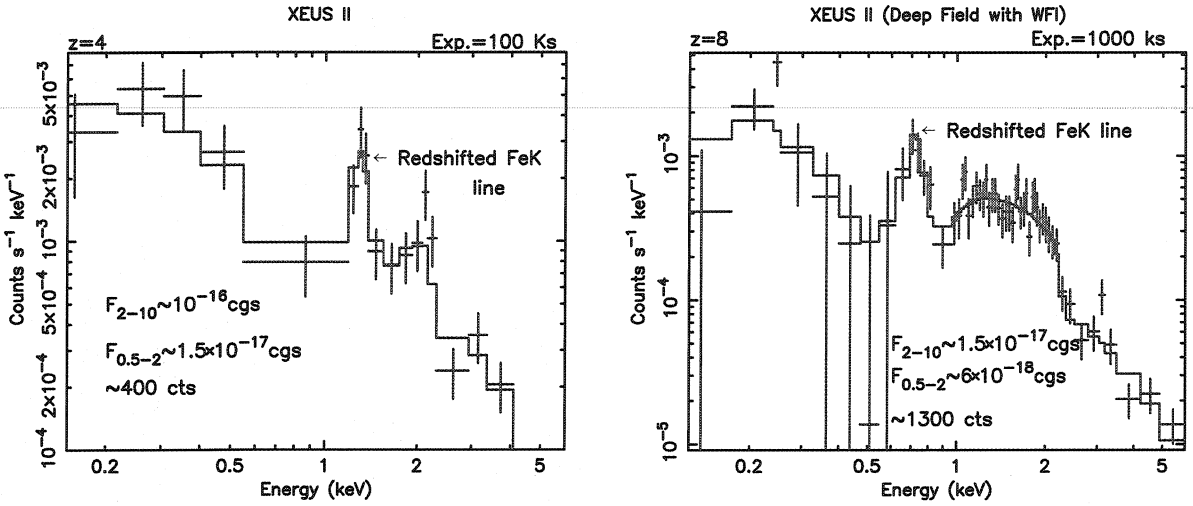


Figure 3. Simulated XEUS spectra of AGNs at redshifts of 4 (left) and 8 (right)

Figure 3 (a) shows a simulation of the detection of the redshifted Fe-K line from a primeval black-hole accretion disc in an exposure of 100 ksec, assuming a 10^{44} erg s^{-1} AGN located at $z = 4$, while (b) shows the same object out at $z = 8$, but now for a 1 Ms exposure.

2.2 Structure formation

Figure 4 (left panel) displays the XEUS performance for measuring the most prominent diagnostic emission lines in galaxy groups and clusters as a function of redshift (5σ detection in 100 ks). The red line shows the sensitivity of XEUS2 in 100 ks to the detection of metal emission lines from clusters and groups of galaxies at different redshifts. The red dotted line is the sensitivity to detecting just the α elements. The shaded areas show the parts of the temperature – redshift plane inaccessible due to absorption in our own Galaxy for column densities of 1 and 3 x 10^{20} atom cm^{-2}. At the lower temperatures, the detection of the Fe-L lines, as well as lines from hydrogenic and helium-like oxygen, govern the limiting sensitivity, whereas at higher temperatures the line emission is dominated by Fe-K and K-shell emission from the mid-Z elements (assumed abundance 0.3 solar). The data points represent the six most distant X-ray selected clusters for which a temperature estimate is available. Figure 4 (right panel) shows a simulated image of a Hickson-type group at a redshift of 2.

As is apparent from Figure 4, the sensitivity of the fully deployed XEUS matches rather well the fundamental limits due to the interstellar absorption. Moreover, due to the very steep dependence of the limiting redshift on source temperature (i.e. luminosity or mass), there is no real gain in spectral sensitivity in the case where the telescope area is further increased by a factor 3 or 5. Therefore, a fully deployed XEUS provides, in a sense, the definitive X-ray observatory for cluster astrophysics: it allows the

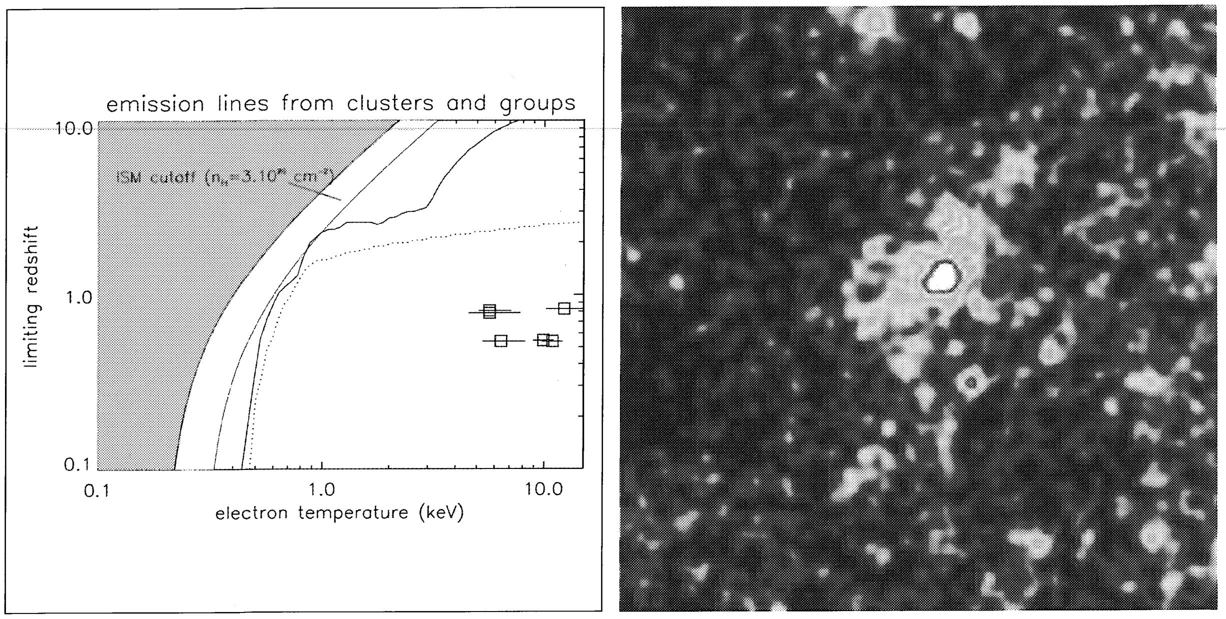


Figure 4. Sensitivity of XEUS to measure the prominent emission lines in galaxy groups and clusters (left panel), the simulated image of a Hickson-type group of galaxies with a luminosity of 10^{43} erg s^{-1} at z=2 (right panel)

assessment of structure formation on a supragalactic mass scale to the extent nature permits from our viewing point in the Galaxy.

Figure 5 shows a simulated spectrum of a galaxy group with a temperature of 1.5 keV and an abundance of 0.3 solar, located at z = 2. It clearly demonstrates the impressive power of XEUS to obtain detailed spectra of low-luminosity clusters at high redshift.

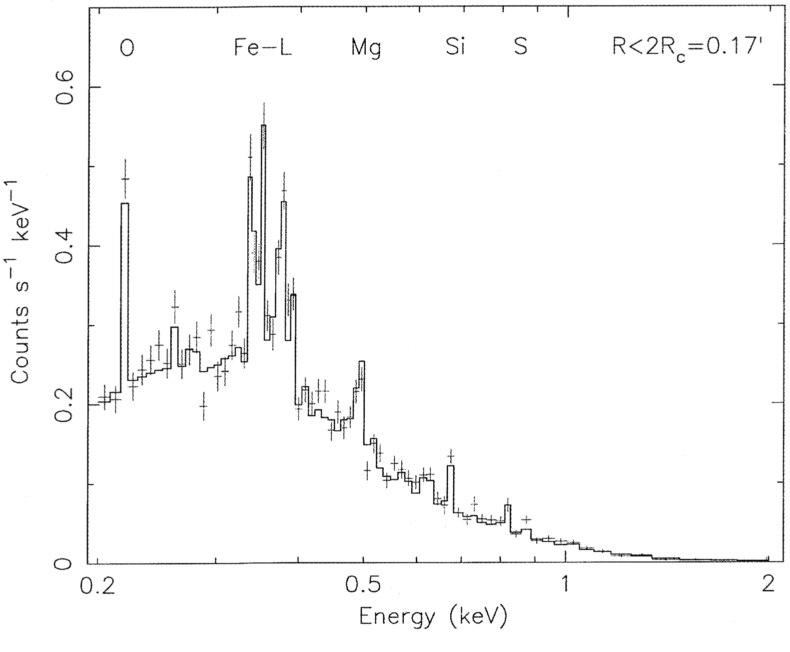


Figure 5. The spectrum of a 10^{43} erg s^{-1} galaxy group at a redshift of 2 based on the simulation shown in Figure 4 (right panel)

3 The Mission Profile

3.1 Basic design features

To achieve the ambitious scientific goals of XEUS a radically different approach needs to be adopted compared to previous X-ray astrophysics missions. 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 optic will capitalize on the successful XMM-Newton Wolter I mirror technology and the industrial foundations which have been already laid in Europe for this programme. 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 subdivided into sectors. The basic mirror unit therefore consists of a set of heavily stacked thin mirror plates, each retaining the correct Wolter I geometry (see Figure 6). The mirror unit consists of a so-called "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 7(a), while the distribution of petals across the very large XEUS aperture is shown in Figure 7(b).

The effective area of such a mirror system in its initial (XEUS1) and fully grown (XEUS2) configurations is shown in Figure 8(a) as a function of photon energy. Note the extremely large increase in effective area below 2 keV after the mirror growth at the International Space Station (see Sect.3.3). It is only after the growth at these critical redshifted energies that studies of the very early Universe will enter a new phase of unprecedented sensitivity.

Table 1. XEUS Baseline: Design Goals

Parameter	Specification(Goal)
Energy range	0.05-30 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 (HEW)	5 " (2")
Fields of view	5 (10) arcmin (WFI), 0.5 (1) arcmin (NFI)
NFI energy resolution @ 1 keV, 8 keV	< 2 eV, < 5 eV
WFI energy resolution @ 1 keV	50 eV
Mission lifetime	> 25 years
Orbit	LEO

NFI = Narrow Field Imaging spectrometer : WFI = Wide Field Imaging spectrometer
Data [ ] refer to the initial "zero growth" configuration prior to the docking at the ISS.

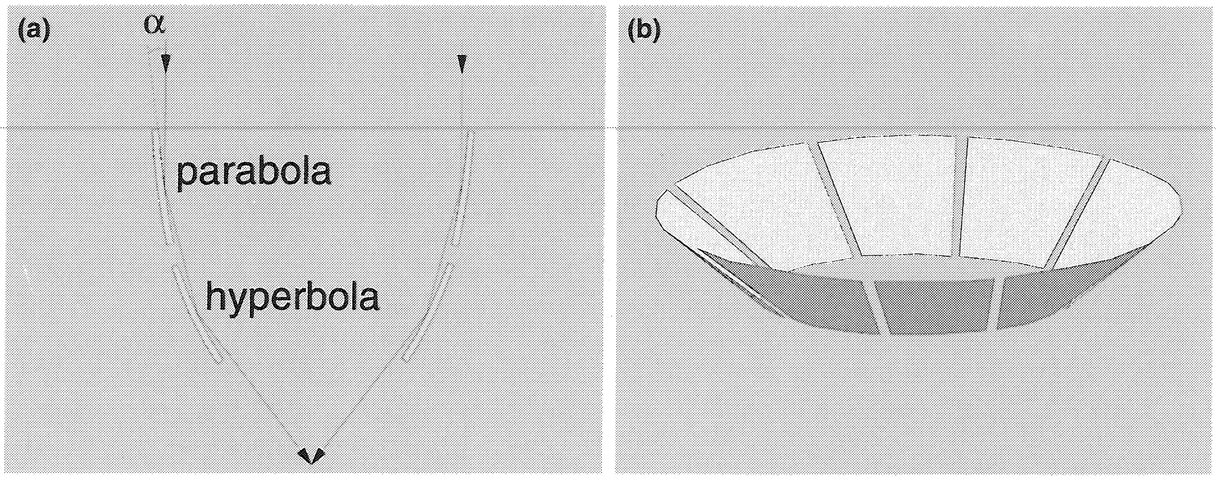


Figure 6. (a) Schematic of the Wolter I optics geometry for a single shell and (b) the same shell after the aperture has been divided into separate segments

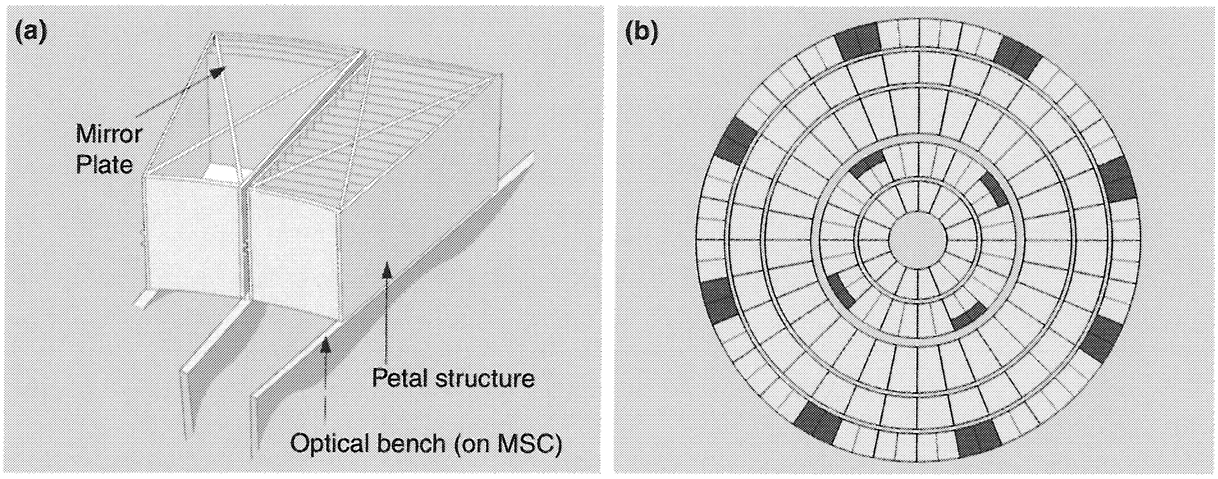


Figure 7. (a) A schematic of a XEUS mirror petal, (b) the distribution of petals across the full 10 m diameter of XEUS2

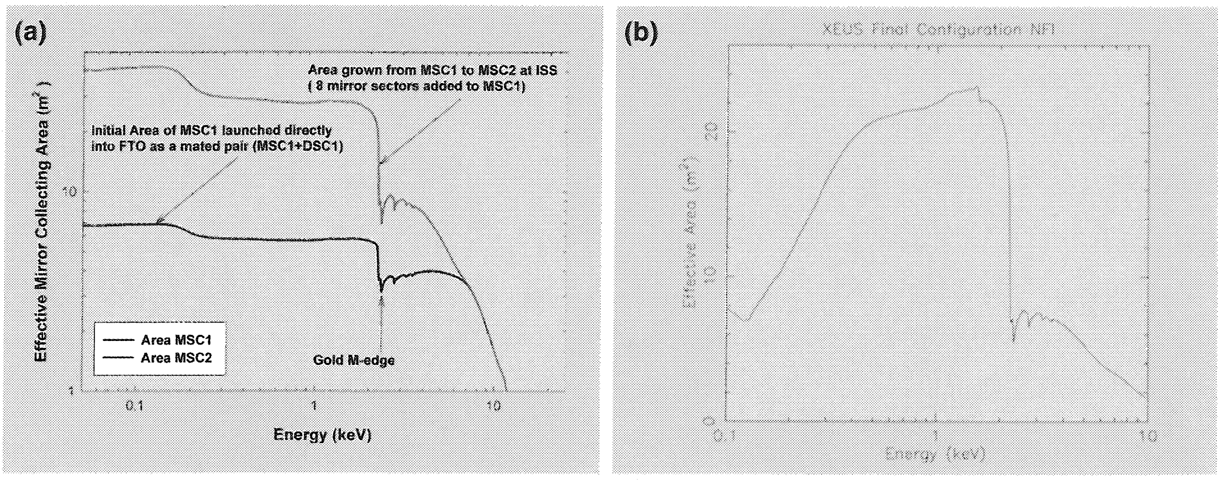


Figure 8. (a) The XEUS mirror effective area for both configurations, (b) The effective area with the focal-plane detectors included

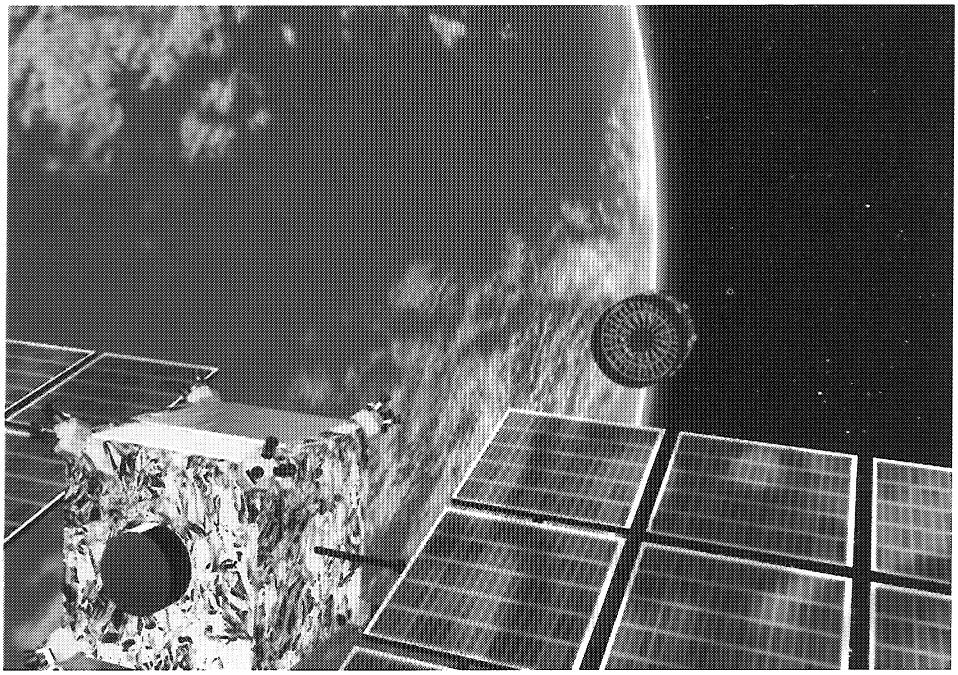
The second key area of the XEUS mission requiring major development is the scientific instrument payload. The model payload comprises three instruments: a Wide Field Imager (WFI) based on semiconductors, and two Narrow Field Imaging spectrometer instruments (NFI). The NFI spectrometers have an energy resolution of < 2 eV at 1 keV as a goal and will be used to provide the detailed spectroscopic studies of specific sources at high redshift which are detected in the WFI deep surveys. The NFI instruments will be based on very-low-temperature sensors, possibly transition edge sensors or superconducting tunnel junctions operating at temperatures of 15-300 mK. The design goals for the XEUS Observatory are summarized in Table 1.

The concept of XEUS envisages two separate spacecraft to accommodate the focal length of 50 m, the mirror spacecraft (MSC) and the detector spacecraft (DSC). An artist's impression of the tandem pair in their operational configuration and orbit – the so-called "Fellow Traveler Orbit" (FTO) to the International Space Station – is shown in Figure 9.

3.2 Initial Mirror and Detector spacecraft configuration

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 celestial calibration

Figure 9. XEUS in its operational configuration. The DSC (foreground) maintains its position at the focus of the MSC mirrors some 50 m away to within ±1 mm



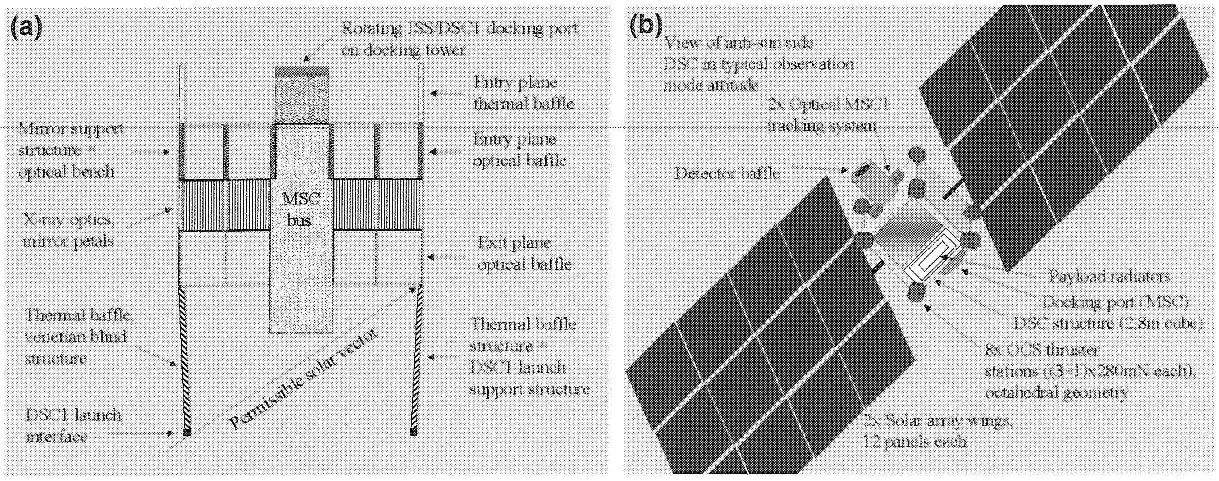


Figure 10. (a) The MSC1 cross-section, (b) The DSC1 perspective view

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 outer and inner diameters of 4.4 and 1.3 m, respectively. The central core is not used for petals and is occupied by the spacecraft bus. Provisions on the MSC1 support structure will be made to allow for the expansion of the MSC1 into MSC2 at the ISS. This growth provides a significant increase in the effective area at the most relevant energies for studying the high redshift Universe (below 2 keV). This growth capability is crucial for achieving the ultimate scientific aims of the mission.

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 mirror can be met, essentially distributing the heat uniformly over the circumference of the spacecraft. The MSC will be flying in low Earth orbit, but will not actively control its orbit during observations. The MSC1 will have a complete attitude 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 MSC1. The docking port is located on the mirror entry plane and is mounted on a rotating platform, simplifying the robotic addition of mirror sectors at the ISS. Figure 10(a) shows the MSC1 in cross-section.

The X-ray detectors (NFI+WFI) are the payload of the DSC. The DSC will track the focus of the X-ray telescope (MSC) to within ± 1 mm. This implies that the DSC will be flying in a non-Keplerian orbit.

Figure 10(b) shows a perspective view of DSC1 looking at the anti-solar side, which shows the thermal radiators of the instruments. The solar panels are rotatable along their major axis to maximise the telescope pointing autonomy while maintaining the solar array perpendicular to the Sun. In Figure 10(b) the array normal is tilted 120° from the X-ray optical axis.

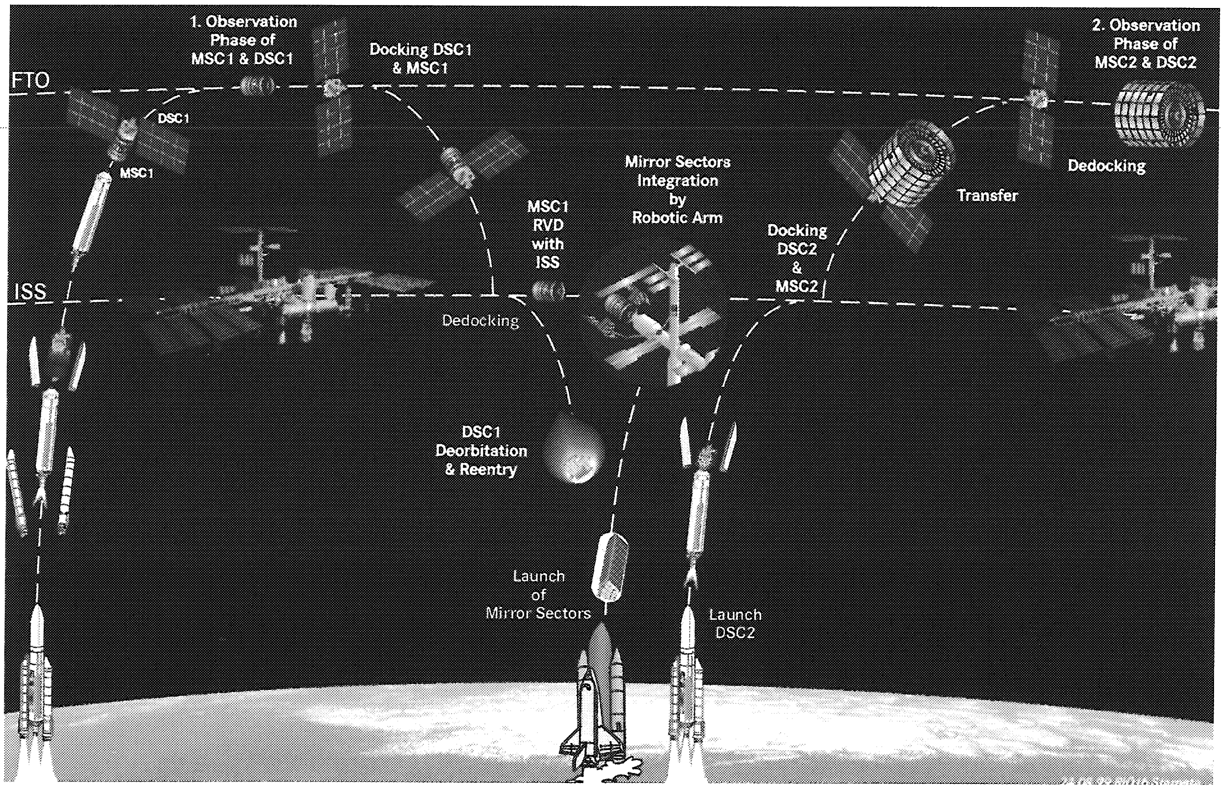


Figure 11. The XEUS mission scenario

3.3 The XEUS mission scenario and logistics

The XEUS mission scenario involving the MSC, DSC, the ISS and associated launchers is summarized in Figure 11.

After the launch of the "zero growth" XEUS into FTO and the commissioning phase, the first observation period begins. These 4 to 5 years can be regarded as a precursor mission for the fully grown XEUS.

DSC1 docks with MSC1 and XEUS lowers its orbit to that of the ISS, DSC1 de-couples from MSC1 and MSC1 visits the ISS, where it docks for upgrading. DSC1 is then de-orbited after the mirror expansion at the ISS. The mirror modules and subsystem components required to build MSC2 can be launched on a single Space Shuttle flight to the ISS. After the separation of MSC2 from the ISS, the new DSC2 is launched into the MSC2 orbit and docks to it. XEUS then returns to FTO, where it resumes its astrophysical observations. At this stage XEUS is sufficiently sensitive to explore the early Universe at X-ray energies at a level comparable to the observations at longer wavelengths performed by NGST, FIRST and ALMA, providing the complementary information needed when studying the evolving Universe.

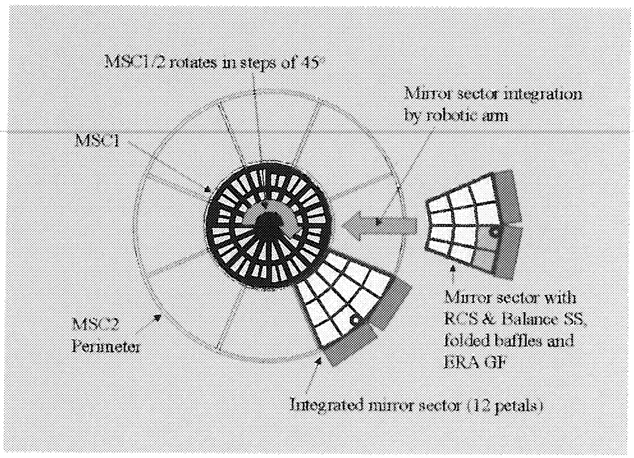


Figure 12. A schematic of the XEUS mirror growth

Note that the mated XEUS1 pair (MSC1+DSC1) is able to wait for up to one year by following the ISS at a safe distance, until the latter is ready to receive the MSC1 for refurbishment and growth. As far as possible, docking technology developed for ESA's Automated Transfer Vehicle (ATV) will be used.

3.4 Interaction with the ISS

In the current baseline scenario, it is envisaged that the mated XEUS1 pair (MSC1 +DSC1) will arrive in the vicinity of the ISS from FTO and the MSC1 will then dock at the ISS using the same docking port as an ATV on the Russian Segment Service Module (RS-SM).

In preparation for the MSC1 visit to the 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. Although a Space Shuttle (STS) could transport the required 8 sectors on one flight, other transport facilities will also need further examination.

Temporary storage of the transport carrier (TC) with the mirror sectors might be required at the ISS, in which case the main truss Z1 storage location could be used. The TC and the mirror sectors will be equipped with the necessary ISS robot arm (SSRMS) and STS robot arm (SRMS) grapple fixtures (see Figures 12 and 13). The mirror sectors will be replaceable into the TC in case of contingencies or emergencies.

The transport of MSC2 to FTO can be performed either using the AOCS of DSC2 or by a dedicated booster motor on MSC2. This needs to be further studied with respect to ISS logistics and fuel consumption.

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.

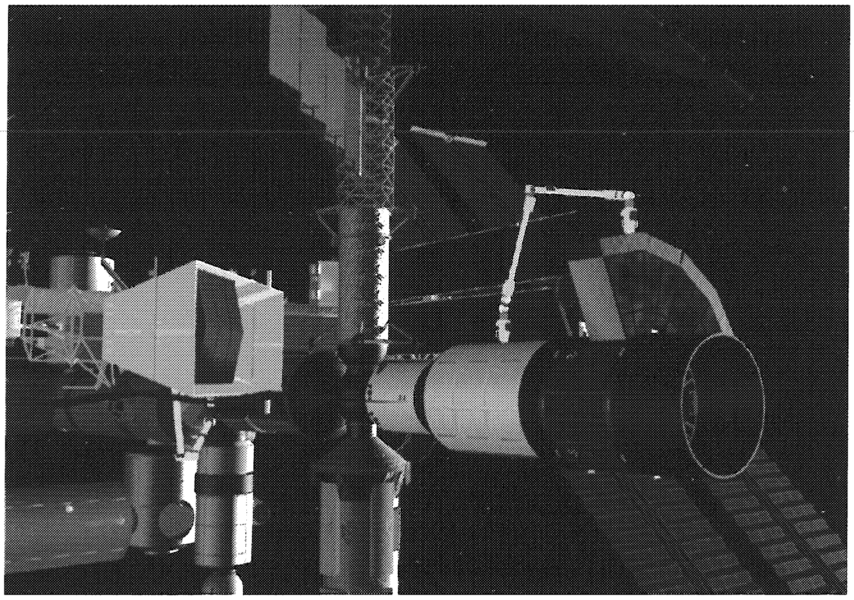


Figure 13. The assembly scenario at the ISS using the European Robotic Arm

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.

4 Programme Status and Outlook: Major Development Items

The ESA XEUS team has conducted an 18 month concept study from 1998 through 1999 with industry led by DASA/D. The purpose of this study was to:

- Establish the overall feasibility of the mission concept elaborated in Section 3.
- Determine those technical and logistical issues which require further detailed study at system and subsystem level.
- Establish an initial cost estimate for the programme.

In addition, and in parallel with these activities, preliminary mirror preparatory technology studies has been initiated with a view to establishing:

- The feasibility of producing through modifications of the XMM-Newton electroforming technology scaled-model individual XEUS-type mirror plates.

- The type of metrology required to screen and establish the optical performance of such plates prior to integration.
- The integration, alignment and fixation approaches required at plate and petal level.
- The design of the petal structure.
- The development of XEUS mandrels capable of providing an X-ray half-energy width on single plates of below 2".
- The optical and X-ray test programme required to demonstrate the performance of petals both on the ground and in-orbit.
- The initial cost estimates of the full development and flight mirror production programmes.

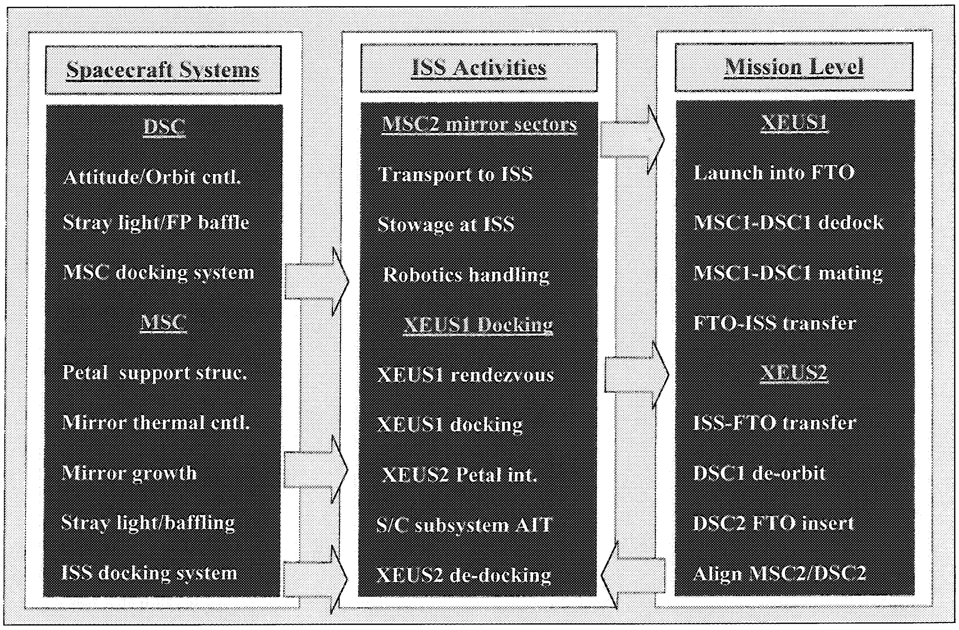
Based on these parallel studies (some involving demonstration hardware), a full system level study can now be conducted. The major issues that will be addressed in such a system study fall into four main categories:

- Mission related specifically to interfaces and logistics for rendezvous at the ISS.
- Spacecraft system and subsystem design.
- Payload technology development and accommodation in the DSC.
- Design and development of the mirror system.

4.1 System development issues

A number of detailed studies are required, which are summarized schematically in Figure 14.

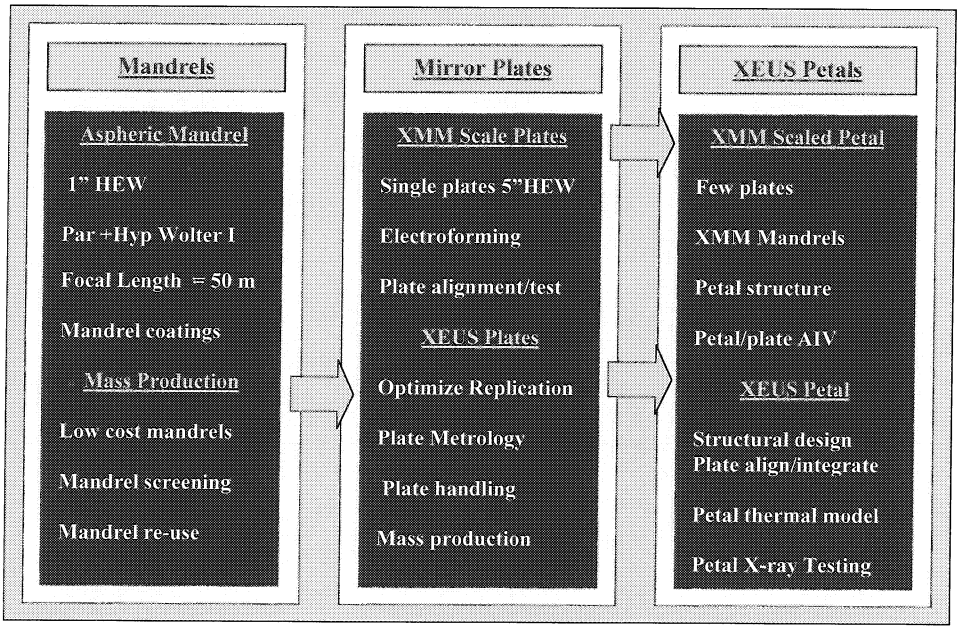
Figure 14. The specific system related studies required during the XEUS preparatory phase



4.2 Mirror technology development

The XEUS mirror is the heart of the mission and, as such, early development is essential. Major technology development will however be required on the basic mirror system so as to demonstrate feasibility. It must be stressed that many of the XEUS mirror requirements are far more demanding than those of the recently launched XMM-Newton replicated optics. A schematic of the overall core mirror activities and technologies needed to be developed over the next few years is shown in Figure 15.

Figure 15. The core mirror activities and associated technologies which need to be developed rapidly during the XEUS preparatory phase



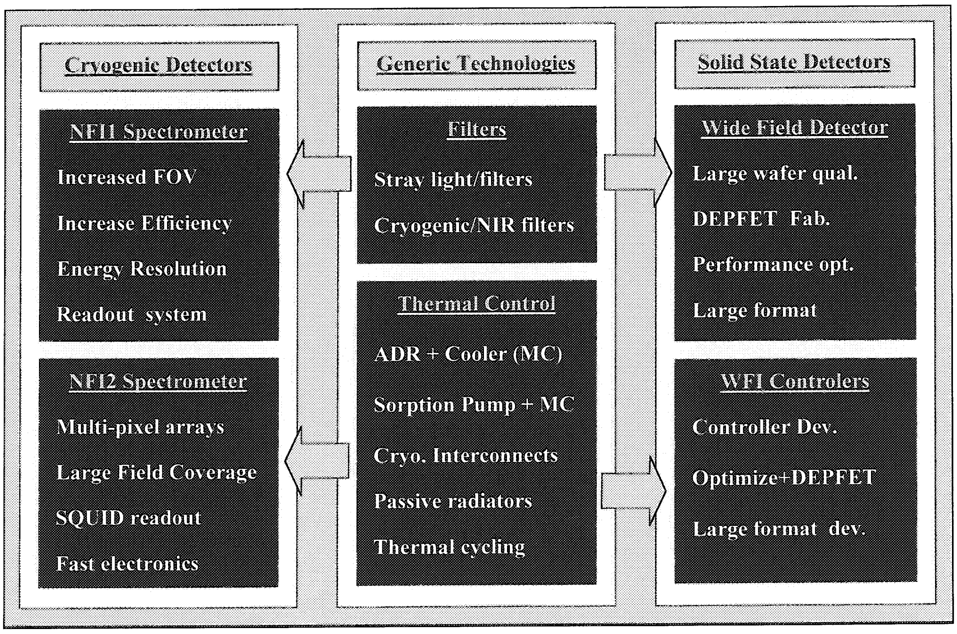
4.3 Payload technology development

Significant technology development will be required on the payload instruments for the DSC over the next few years to ensure the scientific objectives of XEUS can be achieved. Table 2 summarizes the current status of detector development and the goals that need to be reached. A schematic of the overall core technologies that need to be developed during this preparatory phase is shown in Figure 16.

Table 2. **The current status of the detector model payload as compared to the XEUS mission requirements**

Detector Characteristics		Current Status	Requirement
Field coverage	WFI	Small arrays	7 x 7 cm
	NFI1	150 x 150 μm	7 x 7 mm
	NFI2	Single pixel (~0.5 x 0.5 mm)	7 x 7 mm
Energy range	WFI	0.1 – 30 keV	0.1 – 30 keV
	NFI1	0.1 – 3 keV	0.05 – 7 keV
	NFI2	0.1 – 7 keV	0.5 – 15 keV
Energy resolution at 1keV	WFI	~70 eV	50 eV
	NFI1	7 eV	3 eV (Goal: 1 eV)
	NFI2	3 eV	2 eV
Position resolution	WFI	75 μm	75 μm
	NFI1	25 μm (single pixel)	150 μm
	NFI2	Single pixel	240 μm

Figure 16. **The core payload related technologies which need development and demonstration over the during the XEUS preparatory phase**



Conclusion

XEUS represents the logical next step in high-energy astrophysics after the current X-ray observatories complete their operational lives. The XEUS scientific thrusts are founded on a realistic assessment of the key questions that will need to be addressed by the next generation of observatories. The XEUS mission concept is bold but has been shown to be feasible, although substantial technological development will be needed during the early preparatory phase.

The approach of in-orbit growth of a permanent large X-ray mirror making use of the in-orbit infrastructure of the International Space Station and providing through replacement spacecraft a new complement of instruments, ensures that the mission can maintain its scientific relevance deep into the 21st century. Indeed such a mission scenario may well point the way for other astronomy missions in the future.

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