THE XEUS MISSION

Johan Bleeker\(^1\) and Mariano Méndez\(^1\)

SRON, National Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands

Abstract

XEUS, the X-ray Evolving Universe Spectroscopy mission, constitutes at present an ESA-ISAS initiative for the study of the evolution of the hot Universe in the post-Chandra/XMM-Newton era. The key science objectives of XEUS can be formulated as the:

– Search for the origin, and subsequent study of growth, of the first massive black holes in the early Universe.

– Assessment of the formation of the first gravitationally bound dark matter dominated systems, i.e. small groups of galaxies, and their evolution.

– Study of the evolution of metal synthesis up till the present epoch. Characterization of the true intergalactic medium.

To reach these ambitious science goals the two salient characteristics of the XEUS observatory entail:

1. Its effective spectroscopic grasp, combining a sensitive area \(> 20 \text{ m}^2\) below a photon energy of 2 keV with a spectral resolution better than 2 eV. This allows significant detection of the most prominent X-ray emission lines (e.g. O-VII, Si-XIII and Fe-XXV) in cosmologically distant sources against the sky background.

2. Its angular resolving power, between 2 and 5 arc seconds, to minimize source confusion as well as noise due to the galactic X-ray foreground emission.

To accommodate these instrument requirements a mission concept has been developed featuring an X-ray telescope of 50 meter focal length, comprising two laser-locked spacecraft, i.e. separate mirror and detector spacecraft’s. The telescope is injected in a low earth orbit with an inclination commensurate with the ISS, a so-called fellow traveler orbit. At present an on-orbit growth of the mirror spacecraft is foreseen through a robotic upgrade with the aid of the ISS, raising the mirror diameter from 4.5 to 10 meter. The detector spacecraft, formation flying in a non-Keplerian orbit in tandem with the mirror spacecraft will be replaced at 5 year intervals after run-out of consumables with an associated upgrade of the focal plane package.

Key words: Missions: XEUS

1. Introduction

At the end of the 20th century, the promise of high spatial and spectral resolution in X-rays has become a reality. The two major X-ray observatories nowadays operational, NASA’s Chandra and ESA’s XMM Newton, are providing a new, clear-focused, vision of the X-ray Universe, in a way that had not been possible in the first 40 years of X-ray astronomy. These two missions complement each other very well: Chandra has a \(\lesssim 0.5\) arcsec angular resolution and the capability of high spectral resolution on a variety of point sources with the High- and Low-Energy Transmission Grating Spectrometers, while XMM-Newton has a larger spectroscopic area and bandwidth (up to \(\sim 15\) keV), and the capability of high-resolution spectroscopic observations on spatially extended sources.

Despite their superb capabilities, these two missions cannot be used for detailed studies of objects at very high redshifts \((z \gtrsim 5)\). At present, the Chandra and XMM-Newton deep surveys in very narrow pieces of the sky allow us to detect quasars up to redshifts of 6.28, \(\text{[Brandt et al. 2002]}\), but we are not able to produce X-ray spectra of these objects at such distance.

Both Chandra and XMM-Newton are expected to be operational for the next ten years. This is the typical timescale for a new mission to be planned and developed, therefore this is the time to assess what is the future of X-ray astronomy, and to start planning for Chandra’s and XMM-Newton’s follow-up. ESA’s response to this challenge has been cosmology, and the unique role that X-ray astronomy can play in studying the formation and evolution of the hot Universe.

2. Science case

Some of the basic cosmological issues that need to be resolved from the observational point of view are:

– What was the physics of the early Universe?

– What is the nature of dark matter?

– How did the large-scale structure form?

– What did form first, massive black holes or stars and galaxies?

– How did galaxies form and evolve, and what was the role of massive black holes in the centers of galaxies?

– What is the history of the baryons in the Universe?

– How and when were the heavy elements created?
There are several missions underway or planned, aimed at tackling some of these questions. ESA's Planck Surveyor Mission (scheduled for launch in 2007) will produce a detailed map of the spectrum of fluctuations of the cosmic microwave background that will allow us to tightly constrain some of the most fundamental cosmological parameters, and will provide us with a better understanding of the physics that governed the early Universe. Observation with Herschel (2007), NGST (2009), and ALMA (2010) will provide us with information about the formation of the first stars in the Universe, and the formation and early evolution of galaxies.

However, in the course of the evolution of the Universe, most of the baryonic matter must have been heated to temperatures in which it will emit X-rays. Part of this matter, the hottest and denser part of it, is readily detectable in clusters of galaxies, but a large fraction of it at much lower densities, the warm-hot intergalactic medium (Cen & Ostriker 1999), has not yet been observed. Massive accreting black holes, which probably played a central role in the formation and evolution of the galaxies that host them, are only observable in X-rays. Hard X-rays can penetrate the thick clouds of gas and dust in the centers of young galaxies, and therefore observations in these wavelengths are needed to distinguish between energy output from star formation and accretion in these objects.

All of these subjects require very sensitive X-ray instruments, with sufficient angular resolution to avoid confusion at high redshifts, and high energy resolution to be able to study in detail the physical properties of these young objects.

2.1. The first black holes

Deep surveys with XMM-Newton and Chandra are beginning to show that the fraction of galaxies harboring a massive ($\geq 10^6 M_{\odot}$) black hole at its center is larger at redshifts larger than 1 to 3, than it is in the local universe. Previous X-ray and infrared surveys show that the star formation rate and the space density of AGN was a factor of $\sim 100$ larger at redshifts of 2-5 than it is at present. It is not yet clear what is the reason of this recent decline in the star formation rate and the rate at which black holes at the centers of galaxies accrete matter. However, these results indicate that the universe was much more active at redshifts larger than 3 than it is now, and that X-ray emission from those ages is of crucial importance for the proper assessment of evolutionary scenarios.

The current paradigm of structure formation in the Universe [Peebles 1974] states that small-scale objects forms first, and that they afterward merge to form larger ones. Within this scenario, it is not clear whether black holes at the center of active galaxies formed in situ, or whether they grew from accretion of smaller black holes as the smaller galaxies merged to form larger ones. In any case, the tight correlation between the mass of the central black hole and the velocity dispersion of the stars in the bulge of the host galaxy [Ferrarese & Merrit 2000] demonstrates a close relation between massive central black holes and galaxy formation.

Simple cosmological models of hierarchical formation predict the existence of large population of quasars at higher redshifts. Although original results seemed to indicate that star formation rate (and metal production) peaked at a redshift around 1, new estimations that take into account corrections for intrinsic absorption in quasars at high redshifts indicate that the star formation rate increases up to $z \sim 1$, and remains more or less constant above this value [Steidel et al. 1999]. Evidence for a population of high-redshift, highly absorbed, AGN is indicated by ROSAT results (Fig. 1), which show a more or less constant AGN density from $z \sim 1$ to $z \sim 4$ (Miyaji et al. 2000). This is consistent with the fact that hard X-ray observations are much less affected by absorption than optical and UV observations. This means that a large fraction of the high-redshift Universe is obscured. Interalia, it should be noted that some models [Haiman & Loeb 1999] and recent data (Hasinger, private communication), seem to indicate that the space density of AGN might decline
again beyond \( z \sim 4 \). Typical estimates indicate that highly obscured AGN will produce fluxes of \(<10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1}\) in the 2–10 keV energy range. Neither Chandra nor XMM-Newton will be able to measure X-ray spectra at such low flux levels. In order to sample the high-redshift AGN a telescope with a larger spectroscopic effective area is required.

If indeed black holes and AGN were formed at redshifts larger than 5, a question remains as to whether the intergalactic medium at those redshifts was ionized by AGN or by the first massive stars formed in the early Universe, or whether the AGN could have influenced the formation of structure.

Given its expected sensitivity (see below), XEUS will be capable of addressing all these issues. XEUS will be able to detect AGN with central black holes of \( 10^6-7 \text{ M}_\odot \) which emit at luminosities of \( 10^{43-44} \text{ erg s}^{-1}\) at redshifts of 20, and to study their X-ray spectra (via the detection of line emission from Fe Kα) up to redshift of 10. Spectroscopic studies of the Fe line (Fig. 3) and variability studies of the X-ray luminosity of the underlying galaxy will provide information about the geometry of the accretion flow in the vicinity of a black hole, will constrain the geometry close to the black hole’s event horizon, and will allow us to measure the mass, and possibly the spin, of the black holes. By observing a large sample of AGN at different redshifts it will be possible to study the evolution of black hole mass and spin from the early Universe up till now. From the black-hole spin rate history it will be possible to assess the way these black holes formed and grew, given that steady accretion would yield high spin rates, whereas black hole mergers would yield smaller spin rates.

### 2.2. Groups and clusters of galaxies at high \( z \)

In the standard cosmological scenario of hierarchical structure formation, small-scale structures collapse first, and grow into larger aggregates (White & Rees 1978). In a nutshell, dark matter initially accretes into larger and larger halos due to the gravitational amplification of the initial small density fluctuations. Baryonic matter associated to these halos can dissipate energy and cool down by radiation to form stars.

While observations of the CMB (e.g., with the Planck Surveyor Mission) can provide the spectrum of the initial fluctuations, as well as the global parameters governing cosmic evolution, they alone cannot provide information about the physics of gas cooling and heating processes that take place during galaxy formation.

As the baryonic matter collapses and cools, much of the gas will emit soft X-rays. Therefore, it is only through X-ray observations that it is possible to study the hot baryonic matter component within the large scale structure of the Universe. It is through X-ray observations that we have been able to trace the hot plasma bound to the gravitational potentials of groups and clusters of galaxies,
the largest mass aggregates in the Universe. These studies have provided some of the most fundamental constraints to-date used to test cosmological models. X-ray studies of clusters of galaxies have been used to measure the ratio of dark matter to baryonic matter at different length scales, which reflects the way large objects are formed through the hierarchical merging of smaller units, but also has allowed us to trace the abundance of iron and other heavy element in intergalactic space, which seems to imply a much more violent starburst history than previously assumed.

However, because of the limitations of XMM-Newton and Chandra, so far these studies could only be carried out for objects in the local Universe; similar studies at large redshifts, which could provide evidence for evolution from the early Universe up till now, require much higher sensitivity than current missions can provide. The large effective area and high angular resolution of XEUS will enable these studies to be extended to redshifts of $z \gtrsim 2$, to study groups and clusters of galaxies at the epoch when these massive objects first emerged (Venemans et al. 2002), presumably when the star formation rate, and the production of heavier elements, peaked.

These observations will provide a better understanding of the role of feedback from the cluster galaxies to the physical and chemical state of the gas at high $z$. For instance, the evolution of the intra-cluster medium is not purely governed by gravitational effects. Galaxies are injecting metals and energy, probably at early epochs via supernova driven winds (Madau, et al. 2001); this feedback is likely to affect cluster formation and evolution. Central cooling in the early dense groups and cluster cores can have an important effect on the evolution of these systems. Additionally, by tracing the outer parts of clusters and studying the larger scale structures, such as filaments, we expect to observe the growth of clusters of galaxies by accretion of intergalactic matter.

Deep X-ray observations will test the hierarchical formation scenario from merging activity at high $z$ and the evolution of sub-clustering with $z$. For instance, the collision of two sub-clusters should be manifest in temperature maps, through heated gas between the sub-clusters before the collision as well as steep temperature gradients (changes by factor of 2–3 over 200 kpc) at the shocks formed during the collision. The velocities of the gas can range from 200–2000 km/s.

It is important to notice that the history of the gas and galaxy formation are deeply interconnected. During galaxy formation, the temperature, density, and chemical composition of the gas are fundamental in determining the fate of the collapsing gas: it is critical whether the gas can cool or not. X-ray studies are the most direct way to obtain information on the physical state of the gas, which ultimately controls the overall history of galaxy formation.

XEUS will have the angular resolution and sensitivity to study the dynamics of the gas in those systems in detail,
as well as the spectral resolution to measure the mass motion from emission line spectroscopy.

But the hot plasma in clusters of galaxies is probably a small fraction of all the baryonic matter in the Universe. Numerical simulations predict that 30–40% of the baryons are in the warm-hot intergalactic medium, and therefore their radiation is too faint to be detected. However, absorption features against a bright source in the background (e.g., gamma-ray bursts may in principle be detected at redshift of 10 or more) can make them visible (Fig. 3), as is well known from the classical Lyman-α forest spectroscopy. If the temperature of this matter is $> 10^5$ K, the corresponding absorption features lie in the X-ray range, the “X-ray forest” (Hellsten et al. 1998; Perna & Loeb 1998).

Recent hydrodynamic cosmological simulations (Hellsten et al. 1998) show that the strongest absorption features from the intergalactic medium should be produced by O-VII and O-VIII; for an IGM with a metallicity 10% solar, the absorbers that may be detectable given Chandra and XMM-Newton sensitivities have temperatures in excess of $10^{5.5} - 10^{6.5}$ K and overdensities $\delta \gtrsim 100$ (Chen et al. 2002). To be able to sample the IGM over a larger range of temperatures and overdensities, and to be able to detect other elements besides oxygen, a mission with the characteristics of XEUS is needed (Chen et al. 2002).

2.3. Heavy elements enrichment history

One of the fundamental issues in astrophysics today is how heavy elements formed, and what is the evolution of the metallicity of the intergalactic medium. This is strongly related to the star formation history, the possible variations of the initial stellar mass function with environmental conditions, and the circulation of matter between the different phases of the Universe.

This issue will be addressed in part by constraining the history of star formation rate using NGST, Herschel, and ALMA. However, the X-rays provide the best possible way of studying the history of heavy element production. Clusters of galaxies are the largest closed systems where the chemical enrichment process can be studied in detail. X-ray observations of lines emitted by the hot intracluster medium can be used to determine abundances up to much higher redshifts than possible via optical observations of normal galaxies (Fig. 3), with the advantage that X-ray observations provide direct measurement of the abundances, without having to rely on the indirect indicators used in the optical to estimate the element abundances in galaxies.

Abundance gradients in clusters and groups of galaxies can be used to directly assess the chemical enrichment history of the intergalactic medium, much better than would be possible using individual galaxies. Abundances in very poor groups can be measured to any redshift using X-ray absorption line spectroscopy as long as a bright background source can be found. In the case of Gamma-ray burst afterglows this is also true for the host galaxy and all intervening systems. XEUS will measure the abundances of all astrophysically abundant elements, down to the photon detection limit. Since XEUS’ energy resolution will be much better than the equivalent width of the strongest emission lines over a large range of temperatures, it will be possible to obtain information on the heavy element enrichment history of the intracluster medium of a quality now only reached for our Galaxy. This result will have direct implications on our understanding of the evolution of cluster galaxies.

XEUS will make it possible to trace the evolution of the intra-cluster medium abundances back to at least $z \sim 2$, and down to poor clusters, therefore constraining the epoch of production and ejection of the heavy elements, and unveiling the interplay between the dynamical, in particular the effect of mergers, and chemical history of clusters. By comparing the spatial distribution of heavy elements and galaxies up to high redshifts, XEUS will provide a strong constraint on ejection process, wind or ram pressure stripping.

Furthermore, using XEUS it will be possible to probe abundances in the intergalactic medium, and estimate the metal production efficiency of field and cluster galaxies. It will also be possible to independently constrain the star formation history, since the overall cluster metal content is a fossilized integral record of the past star formation, and to precisely measure the abundance relative to Fe back to $z \sim 2$, which can be used to assess the relative importance of type I and type II supernovae and their past rates. This...
is a strong constraint on the initial mass function, and also has far reaching consequences on our understanding of the thermal history of the inter-cluster medium.

3. THE MISSION

The key characteristics of XEUS are large X-ray mirror aperture, high spectral resolution over wide-band energy range, and good angular resolution (see Table 1). With an area larger than 20 m² and an energy resolution of 2 eV below 2 keV, the XEUS final configuration (see below) will be able to significantly detect the most prominent X-ray emission lines of O-VII, SI-XIII and Fe-XXV against the sky background and source continuum, while an angular resolution of 2–5 arcsec will help minimize source confusion and will reduce the background due to galactic foreground X-ray emission.

XEUS will consist of two separate spacecrafts, the mirror and the detector spacecraft, respectively, injected in low-Earth orbit with an inclination equal to that of the ISS (fellow-traveler orbit). The mirror and detector spacecrafts will fly in formation, yielding a 50-m focal length. The detector spacecraft will track the focus of the X-ray telescopes with a precision of ±1 mm per degree of freedom. Because the detector spacecraft will be flying in a non-Keplerian orbit, it will need active orbit control.

XEUS is a two-step mission that will grow in space. XEUS-1, which will be launched by an Ariane 5 rocket, will have a primary mirror of 4.5-m in diameter comprising two concentric rings with so-called petal structure, each petal consisting of a set of heavily stacked thin mirror plates with a Wolter I type geometry. After five years in space, the mirror spacecraft will dock with the ISS, where the European Robotic Arm will be used to add additional mirror segments around the central core, so the XEUS mirror will grow to its final size, 10-m in diameter (Fig. 6). The construction of the mirrors poses several technological challenges, among them the manufacturing of the mirror plates and their integration into modules, and the integration of the individual modules in space into the final configuration ensuring the required angular resolution of 2 to 5 arcsec. Alternative mission profiles, e.g. Ariane 5 launch of the complete XEUS in low-Earth orbit, are also being studied in case the necessary ISS infrastructure is not available.

The instrument payload model presently comprises a Wide-Field Imager (WFI), and two Narrow-Field Cameras (NFC), one of them optimized for soft X-rays and the other for hard X-rays. The WFI is based on pn-CCD technology, with an energy resolution of 50 eV at 1 keV. The WFI CCD covers 5' × 5', and has a count rate capability with low pile-up (<5% of up to ~1000 count s⁻¹) within the PSF (HEW). The NFC is based on Superconducting Tunnel Junctions (the soft-X camera) and Transition Edge Sensors (the hard-X camera) technologies, will cover 30' × 30', and will allow for a time resolution of less than 5 microseconds. The energy resolution will be better than 2 eV at 1 keV for the soft NFC, and 2 eV and 5 eV, at 1 keV and 8 keV, respectively for the hard NFC. The high energy resolution required seems feasible, given that at present a single pixel micro-calorimeter can achieve an energy resolution of 3.9 eV at 5.9 keV, with a thermal response of 100 microseconds.

When XEUS grows to its final configuration, the detector spacecraft will be replaced with a new generation of instrument technology. XEUS expected lifetime is 25 years or more.

The main characteristics of XEUS are indicated in Table 1. Given those specifications, XEUS will be able to detect a source at a flux of 4 × 10⁻¹₈ erg cm⁻² s⁻¹ in the 0.5–2 keV energy range in a 100 ks exposure, and it will be capable of measuring spectra down to a flux of 10⁻¹⁷ erg cm⁻² s⁻¹. In order to achieve these fluxes, the Half-Energy Width of the PSF must be <2–5 arcsec.

4. PRESENT STATUS AND TECHNOLOGY DEVELOPMENTS

Several studies relating to XEUS enabling technologies are currently in progress or have been planned for the near future. An 18-month system level study will be carried out by the ESA directorate for Science and the directorate for Manned Space and Microgravity, with technical support from ISAS. This activity will kick off in April 2002 and

Table 1. XEUS 1/2 design specifications

| Specification                  | XEUS-1 | XEUS-2 |
|-------------------------------|--------|--------|
| Energy range                  | 0.05 – 30 keV |        |
| Effective area @ 1 keV        | 6 m²   | 30 m²  |
| Effective area @ 8 keV        | 3 m²   | 2 m²   |
| Angular resolution (HEW)      | 5”     | 2’     |

Specifications that do not change in XEUS-2 are not indicated.
will address several basic feasibility issues concerning telescope configuration, orbit, ISS interfacing and flight implementation scenarios. More specific studies, targeted at formation flying (station keeping), robotic assembly techniques, optical/IR straylight suppression filters, and 50-milli-Kelvin closed cycle coolers are now being addressed in the ESA Technology Research Programme (TRP). Under the TRP, two X-ray sensor study contracts, one related to the Wide-Field active pixel detector array and one dealing with a squid-read-out X-ray bolometer/TES array, will be started at the beginning of 2002, based on quite promising single-pixel results obtained in various European (space) research institutes.

The major development item for the coming years is obviously the technology, metrology, assembly, and active alignment of the X-ray mirror petal. Starting from the XMM replica technology, several alternative routes for manufacturing are now being pursued, including the application of new, lightweight, materials like slumped glass and SiC. Since the mirror technology is at the very heart of the XEUS feasibility, it has been designated as a core technology development in the ESA science programme, implying major development funding in the period 2002-2004. These efforts will be part of the so-called Core Technology Programme, which was recently established within ESA science for strategic technology investments.

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