Polarimetry with XEUS

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Scientific Goals of XEUS

• Study the formation of the first gravitationally bound, dark matter dominated, systems and track their evolution to the massive clusters: features in small clusters at z>1.

• Study the evolution of metal synthesis down to the present epoch. ICM is less sensitive to local spread.

• Characterise the mass, density, temperature and metallicity of Inter Galactic Medium. Absorption Spectroscopy on luminous high Z QSO and GRB afterglows.

• Detect massive black holes in the earliest AGN and estimate their mass and spin

To be achieved with

• A spectroscopic area >20 m² below 2keV

• An angular resolution <5 arcseconds to resolve background

• A spectral resolution of 2eV sufficient for photon-limited detection of the most prominent emission lines (O VII, Si XIII, Fe XXV etc.)
X-Ray Evolving Universe Spectroscopy

• A mission under study by ESA

• Very large area optics (the X-ray equivalent of Keck and LVT) with <5 arcsec resolution

• High spectroscopic capabilities

• The Optics and the Focal Plane: 2 independent Satellites at 50 m distance
A program in two phases

XEUS-1: the core of 6 m² area to be launched first

After 5 years 8 more sectors will be added to the core to extend the area to 30 m² (mainly at low energies)

Also the focal plane will be upgraded

The orbit is selected to make possible the integration of XEUS-2 in the space

The project was conceived to be based on ISS (!!)
General strategy of XEUS mission
## XEUS Orbit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude (km)</td>
<td>600</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0</td>
</tr>
<tr>
<td>Inclination (deg)</td>
<td>51.6</td>
</tr>
<tr>
<td>Period (min)</td>
<td>97</td>
</tr>
<tr>
<td>Maximum eclipse (min)</td>
<td>35.5</td>
</tr>
<tr>
<td>Node spacing (deg)</td>
<td>24</td>
</tr>
<tr>
<td>Node precession (deg day⁻¹)</td>
<td>-4.5</td>
</tr>
<tr>
<td>De-orbit ΔV (m s⁻¹)</td>
<td>256</td>
</tr>
<tr>
<td>Altitude change ΔV (m s⁻¹ km⁻¹)</td>
<td>0.54</td>
</tr>
<tr>
<td>Plane change ΔV (m s⁻¹ deg⁻¹)</td>
<td>132</td>
</tr>
<tr>
<td>Earth angular radius (deg)</td>
<td>66</td>
</tr>
<tr>
<td>Range to horizon (km)</td>
<td>2831</td>
</tr>
</tbody>
</table>
XEUS Instrument Working Group

Didier Barret, CESR Toulouse, France
Marcos Buvdaz, ESA/ESTEC, The Netherlands
Carl Budtz-Jorgensen, DSRI, Denmark
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The evolution of X-ray optics
according to Bavdaz & Peacock 2002

Table 1. A summary of the principal characteristics of Wolter-I X-ray mirror systems flown to date*

<table>
<thead>
<tr>
<th>Mission</th>
<th>Agency</th>
<th>Launch (yr)</th>
<th>Lifetime (yr)</th>
<th>Mass (kg)</th>
<th>Nest</th>
<th>Focal Length (m)</th>
<th>Number Modules</th>
<th>Aperture (cm)</th>
<th>FOV (arcmin)</th>
<th>R (arcsec)</th>
<th>Area (cm²) @ 1 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Einstein</td>
<td>NASA</td>
<td>1978</td>
<td>2.5</td>
<td>~460</td>
<td>4</td>
<td>3.5</td>
<td>1</td>
<td>56</td>
<td>75</td>
<td>~2</td>
<td>1x200</td>
</tr>
<tr>
<td>Exosat</td>
<td>ESA</td>
<td>1983</td>
<td>3</td>
<td>7</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>30</td>
<td>120</td>
<td>~18</td>
<td>2x35</td>
</tr>
<tr>
<td>Rosat</td>
<td>DLR</td>
<td>1990</td>
<td>9</td>
<td>950</td>
<td>4</td>
<td>2.4</td>
<td>1</td>
<td>84</td>
<td>120</td>
<td>1.7</td>
<td>1x400</td>
</tr>
<tr>
<td>BeppoSax**</td>
<td>ASI/NIVR</td>
<td>1996</td>
<td>6</td>
<td>13</td>
<td>30</td>
<td>1.85</td>
<td>4</td>
<td>16</td>
<td>30</td>
<td>60</td>
<td>1x480</td>
</tr>
<tr>
<td>Chandra</td>
<td>NASA</td>
<td>1999</td>
<td>~5–10</td>
<td>956</td>
<td>4</td>
<td>10</td>
<td>1</td>
<td>120</td>
<td>30</td>
<td>0.5</td>
<td>1x750</td>
</tr>
<tr>
<td>Newton</td>
<td>ESA</td>
<td>1999</td>
<td>~5–10</td>
<td>350</td>
<td>58</td>
<td>7.5</td>
<td>3</td>
<td>70</td>
<td>30</td>
<td>12</td>
<td>3x1500</td>
</tr>
<tr>
<td>XEUS</td>
<td>ESA</td>
<td>&gt;2012</td>
<td>~25</td>
<td>?</td>
<td>?</td>
<td>50</td>
<td>1</td>
<td>1000</td>
<td>5</td>
<td>2–5</td>
<td>1x300 000</td>
</tr>
</tbody>
</table>
A single "lens" of 10m Ø cannot be launched in space. It must be built in orbit. This implies the loss of the cylindric symmetry and multiplies the technical challenges.
Effective Area for XEUS 1&2

- Area grown from MSC1 to MSC2 at ISS (8 mirror sectors added to MSC1)
- Initial Area of MSC1 launched directly into FTO as a mated pair (MSC1+DSC1)
- Gold M-edge

Effective Mirror Collecting Area (m²)

Energy (keV)
Detecor Satellite

View of anti-sun side
DSC in typical observation
mode attitude

2x Optical MSC1 tracking system

Detector baffle

Payload radiators
Docking port (MSC)
DSC structure (2.8m cube)

8x OCS thruster stations ((3+1)x280mN each),
octahedral geometry

2x Solar array wings,
12 panels each
# XEUS Focal Plane Instruments Baseline

<table>
<thead>
<tr>
<th>Parameter</th>
<th>WFI</th>
<th>NFI1</th>
<th>NFI2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector type</td>
<td>Active Pixel DEPFET</td>
<td>STJ</td>
<td>TES</td>
</tr>
<tr>
<td>Field Coverage</td>
<td>5 arcmin</td>
<td>30 arcsec</td>
<td>32 arcsec</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>1000 x 1000</td>
<td>48 x 48 (option 1 of 3)</td>
<td>32 x 32</td>
</tr>
<tr>
<td>Pixel size (arcsec)</td>
<td>0.3</td>
<td>0.6</td>
<td>1</td>
</tr>
<tr>
<td>Energy resolution (eV)</td>
<td>125 eV</td>
<td>3 (&lt; 1) eV</td>
<td>2 &amp; 5 eV</td>
</tr>
<tr>
<td></td>
<td>@ 6 keV</td>
<td>1 keV</td>
<td>1 &amp; 8 keV</td>
</tr>
<tr>
<td>Detection efficiency (%)</td>
<td>100% @ 6 keV</td>
<td>90% @ 1 keV</td>
<td>&gt;90% @ 6 keV</td>
</tr>
<tr>
<td>Time resolution</td>
<td>&lt; 5 ms</td>
<td>&lt; 5 μs (&lt; 1 ms)</td>
<td>&lt; 5 μs</td>
</tr>
<tr>
<td>Count rate limit</td>
<td>200-1000 Hz/PSF</td>
<td>25000 Hz/PSF</td>
<td>250 Hz/PSF</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>180 (210) K</td>
<td>300 (30) mK</td>
<td>35 (20) mK</td>
</tr>
</tbody>
</table>

( ) option to be decided during technology demonstration phase
APS concept for WFI

A Si DEPFET 500 µm thick
1000_1000 pixel
75_75 µm^2
Read-out 1000 Hz
The spectral resolution is improved to the Fano limit because the read-out is non-destructive and the e-noise is averaged many times
Operated at 220 K
NF11: the Narrow Field Soft X-ray Imaging Spectrometer

An array of Josephson junction detectors

Energy resolution is ~2 times the specified one (<2eV at 500eV) and 2 techniques are under study to extend the present arrays to the required dimensions of 48_48

A read-out matrix prototype (12_8) based on V with Nb plugs and wires. Should be extended to 24_24
NFI2
A Microcalorimeter equipped with a Transition Edge Sensor

Requirements

Space resolution: 1arcsec (240µm); 32_32 pixels

FWHM: 2eV @ 1 keV; 5eV @ 7 keV

Status

The requirements can be fulfilled at level of individual chip.

Different techniques (time division multiplexing, frequency division multiplexing) to make arrays under study in several parts of the world

Micrograph of a TES/absorber at SRON

3.9 eV FWHM at 5.9KeV

E.Costa:X-ray Polarimetry workshop SLAC 9-11February 2004
Auxiliary instrumentation

The Ideology

The primary aim of XEUS is to study the astrophysics of some of the most distant and hence youngest known discrete objects in the Universe.

But if you have such a telescope in orbit a lot of other science can be done!

Therefore following a workshop on March 11-13 2002 the Steering Committee has decided to add to the mission study some auxiliary instruments:

• An extension of a sector of the optics to higher energies, with a CdTe or a CZT array below the WFI high energy spectra

• Large area CCDs covering all the focal plane surveys

• A silicon drift chamber for high frequency timing of very bright sources BH, NS physics

• A polarimeter big science!
Hard-X Camera

Figure 9.1.5. Schematic of the CdTe pixel detector for the HXC. Four detectors, each 2 x 2 cm, will be tiled. Three ASICs will be mounted below the CdTe crystal to process the signal.

Figure 9.1.6. Schematic of the CdTe pixel detector.
XEUS 1&2 provide a collection area 10 times and 50 times better than XTE/PCA. This may provide a breakthrough in science of Neutron Stars and BH by timing analysis. A fast detector capable to handle rates of the order of MHz is needed. Silicon Drift Chamber is the best candidate.
To achieve a high counting rate (up to 1Mc/s) with detectors that can handle up to 100 kc/s while preserving a good spectral resolution (200 eV) an array of 19 SDD of 5 mm² is located out of focus.
Possible focal plane lay-out

The swap from one instrument of the focal plane to the other is actuated by the alignment control of the two satellites.

The first scientific driver of the assessment is to maximize the observing time of the WFI.

For the Polarimeter (and SDD) the requirements in terms of temperature and baffling are very moderate and the assumption is that it will work a limited fraction of the time so it will be positioned somewhere and won’t be a driver of the trade-off.
A polarimeter based on the Photoelectric Effect

The photo-electric effect is very sensitive to photon polarization

Distribution in space of K-shell photo-electrons after the absorption of a polarized photon beam.
Imaging the Photoelectron with a finely subdivided detector

Polarization information is derived from the track of the photoelectrons imaged by a finely subdivided gas detector

E.Costa: X-ray Polarimetry Workshop SLAC 9-11 February 2004
The Micropattern Gas Detector
Algorithms

- reconstructed photoemission direction
- reconstructed absorption point
- barycentre
- principal axis
The angular distribution

5.9 KeV unpolarized source

\[ MDP(n_\sigma) = \frac{1}{\varepsilon \mu} \cdot \frac{n_\sigma}{S} \cdot \sqrt{\frac{2 \varepsilon S + B}{AT}} \]

5.4 KeV polarized source

\[ C(\phi) = A + B \cdot \cos^2(\phi - \phi_0) \]

Modulation factor = \((C_{\text{max}} - C_{\text{min}}) / (C_{\text{max}} + C_{\text{min}}) \sim 50\% \text{ at } 5.4 \text{ KeV}\]
From present prototypes to an actual mission

A long development phase is foreseen

A new polarimeter is developed evolving the present prototype by:

Increasing the absorption thickness of the gas and choosing a mixture suitable to minimize the diffusion that smears the track.

Decreasing the pixel size down to possibly 50 µm.

Choosing a mixture that produces straighter tracks.

Improving the pattern recognition algorithms.
Status of the art
see the talk by R. Bellazzini
An event
A Conservative Configuration for XEUS-1

Filling Gas: Ne 80% DME 20% 1Atm
Window: Beryllium 50µm
Conversion/Drift Gap: 10 mm
GEM thickness: 50 _m gold clad kapton
GEM hole: 40 _m diameter, 60 _m pitch
Drift Voltage (Window to GEM): –1000 V
GEM voltage: 600 V
Readout pixel: 100 _m
Pixel: 16000 on hex pattern
Diameter: 14 mm (f.o.v. = 1’)

This is very close to something that exists or is a moderate extrapolation

The effective area

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Ingredients for simulations

![Graph of Gas efficiency vs. Energy (keV)]

![Graph of Modulation Factor vs. Energy (keV)]
Virtually a background-less experiment

In Neon filled detectors background from OSO-8 (A.Bunner ApJ 1978) is:

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Counts/cm² s keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75 – 1.6</td>
<td>$3.8 \times 10^{-4}$</td>
</tr>
<tr>
<td>1.6 – 3.0</td>
<td>$1.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>3.0 – 6.0</td>
<td>$1.0 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Also accounting for a worse orbit and for a worse background discrimination the background within a PSF will be $< 3 \times 10^{-4}$ c/s.
A body similar to SAX – MECS could be suitable
A body for the new chip
Data handling
<table>
<thead>
<tr>
<th>Source</th>
<th>Expected Counting Rate (c/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Very Bright</strong></td>
<td></td>
</tr>
<tr>
<td>Crab</td>
<td>27000</td>
</tr>
<tr>
<td>GRS1915+105</td>
<td>20000</td>
</tr>
<tr>
<td><strong>Bright</strong></td>
<td></td>
</tr>
<tr>
<td>HerX-1</td>
<td>1800</td>
</tr>
<tr>
<td><strong>Faint</strong></td>
<td></td>
</tr>
<tr>
<td>Cen A</td>
<td>90</td>
</tr>
<tr>
<td><strong>Very Faint</strong></td>
<td></td>
</tr>
<tr>
<td>BL Lac</td>
<td>12</td>
</tr>
<tr>
<td><strong>Marginal</strong></td>
<td></td>
</tr>
<tr>
<td>Jet from XTE J1550-564</td>
<td>0.13</td>
</tr>
</tbody>
</table>
A criticality: Telemetry

Because of the diffusion the number of pixels fired is always high
Typical counting rates

A faint (for Polarimetry Source): BL Lac a Blazar of \(1.11 \times 10^{-11}\) erg/ cm\(^2\) s (0.5 mCrab) and a power law spectrum (\(\alpha= -1.84\))

\[11.8 \text{ c/s}\]

The brighter MCG-6-30-15 a Seyfert-1 of \(6.3 \times 10^{-11}\) erg/ cm\(^2\)/s (2.5 mCrab) with a power law spectrum (\(\alpha= -2.05\))

\[70 \text{ c/s}\]

A very bright source: Crab
To transmit the whole information

• Transmission of single photon tracks (address and pulse height) of each fired pixel.

• Tagged with 4μs time (Recycle each second)

• Transmission of the position (X, Y) and energy in each fired pixel
To transmit compressed information

- Interaction point and polarization computed aboard
- Position of the interaction point (optional)
- Angle of polarization
- Degree of polarization
- Less bits for time (optional)
- Quality parameters to allow for further rejection
## Results

<table>
<thead>
<tr>
<th>Energy range (keV)</th>
<th>Fired Cells</th>
<th>Area of the subframe</th>
<th>Bit/event (all infos)</th>
<th>Bit/event (reduce d infos)</th>
<th>Bit rate BL LAC (All infos)</th>
<th>Bit rate MCG-6-30-15 (All infos)</th>
<th>Bit rate Crab (All infos) (compressed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-3</td>
<td>13</td>
<td>44.9</td>
<td>427</td>
<td>48</td>
<td>3.3 K</td>
<td>20.7 k 2.3 k</td>
<td>8290 k 932 k</td>
</tr>
<tr>
<td>3-4</td>
<td>16</td>
<td>59.3</td>
<td>542</td>
<td>48</td>
<td>2.1 K</td>
<td>7.4 k 0.85 k</td>
<td>2958 k 253 k</td>
</tr>
<tr>
<td>4-5</td>
<td>20</td>
<td>82.8</td>
<td>730</td>
<td>48</td>
<td>1.7 K</td>
<td>3.7 k 0.34 k</td>
<td>1460 k 96 K</td>
</tr>
<tr>
<td>5-8</td>
<td>35</td>
<td>207.4</td>
<td>1727</td>
<td>48</td>
<td></td>
<td>3.0 k 0.88 k</td>
<td>2050 k 37 k</td>
</tr>
<tr>
<td>8-12</td>
<td>60</td>
<td>538.2</td>
<td>4374</td>
<td>48</td>
<td></td>
<td>1.0 k 0.01 k</td>
<td>397 k 4 k</td>
</tr>
<tr>
<td>2-12</td>
<td>All data</td>
<td></td>
<td></td>
<td></td>
<td>7.1 K</td>
<td>35.8 k 3.28 k</td>
<td>15.2 M 1.35 M 1.74 M</td>
</tr>
<tr>
<td>2-12</td>
<td>Timing + onbard Polarization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-12</td>
<td>Timing + imaging + onbard Polarization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Sensitivity to AGNs in $10^5$ s
MCG 6-30-15
Energy Resolved Polarimetry

<table>
<thead>
<tr>
<th>Band</th>
<th>MDP</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 – 3 keV</td>
<td>1.7 %</td>
</tr>
<tr>
<td>3 – 4 keV</td>
<td>1.5 %</td>
</tr>
<tr>
<td>4 - 5 keV</td>
<td>1.9 %</td>
</tr>
<tr>
<td>5 – 10 keV</td>
<td>2.1 %</td>
</tr>
</tbody>
</table>
Soft Gamma Repeaters: \textbf{SGR1900+14}

On each short bursts (100 ms): 30%

Afterglow after a strong burst: 2.3\% in $5 \times 10^4$ s

In quiescence: 2.2\% in $10^5$ s


\textbf{E. Costa: X-ray Polarimetry Workshop SLAC 9-11 February 2004}
But with XEUS a real space resolved Polarimetry

Micropattern Detectors have a fairly good position resolution, Through the analysis of tracks and the reconstruction of the impact point
Polarimeter in the focal plane (imaging)

The optimal position of the polarimeter is with the focus at mid-height of the absorption gap. The maximum blurring is:

\[ \delta x_{\text{max}} \equiv \frac{D \times h}{2 \cdot f} \]

D = diameter of the telescope, f = focal length, h = absorption gap.

With \( f=50\text{m} \) \( D=4.5\text{m} \) and \( h=10\text{mm} \) \( \delta x_{\text{max}} = 0.45 \text{ mm} \) equivalent to \( 1^{"}.9 \)

For a thicker absorption gap of \( 3 \text{ cm} \) \( \delta x_{\text{max}} = 1.3 \text{ mm} \) equivalent to \( 5^{"}.4 \)

Due to the large scale of XEUS the polarimeter will be an imager as good as any other instruments.
Polarimeter off the focal plane

If a design trade-off of the focal plane requires that the polarimeter is set at a distance different from the focus the same formula applies

\[ \delta x_{\text{max}} \equiv \frac{D \times g}{f} \]

g is the distance from the focus along the optical axis. For \( g=5 \) cm \( \delta x_{\text{max}} = 4.5 \) mm equivalent to 18”

The polarimetric capability is not affected and the imaging capability is worsened of a factor 2-3, but still of high astrophysical interest.
Polarimetry of extended sources

1 acminute f.o.v. is good but more could be better (see the talk by S. Reynolds)
Jets from Superluminal Galactic Sources can be angularly resolved and separate polarimetry of the Jet and of the source is feasible.

On the W-jet we can measure:

- 21% in $10^5$ s
- 7% in $10^6$ s (a lot but not impossible)

Hopefully the final version will do better!
Can XEUS survive to the ISS crisis?

XEUS-1 is anyhow a very powerful instrument.

An operation in LII would make life easier to the ACS and allow for faster operations.

ESA could decide to proceed even out of the ISS frame possibly sacrificing some potentialities.
A cheap concept for the optics

The telescope is built as an assembly of lenses
An X-ray lens

Each lens consists of square multifiber bundles

Each fibre has pores $10 \times 10 \, \mu m^2$
Let us be optimistic

Xeus could be converted into a “conventional” mission based on all expendible items.

If the MCP optics can arrive to the requied 5 arcsec it would help a lot because of the huge reduction of weight.

In any case the X-ray polarimetry cannot jump from OSO-8 to XEUS: a pathfinder intermediate mission is definitely needed.