The XEUS Hard X-ray Camera

C. Budtz-Jørgensen, T. Takahashi, L. Piro, I. Kuvvetli, A. Holland, D. Lumb, P. de Korte

a Danish Space Research Institute, Copenhagen, Denmark
b ISAS, Japan
c IAS, Italy
d University of Leicester, UK
e ESA, Holland
f SRON, Holland

ABSTRACT

The high-energy response of XEUS will be of crucial importance for a number of astrophysical topics, e.g.: highly obscured AGNs, non-thermal emissions from SNRs, AGNs and clusters of galaxies, nuclear line emission from SNRs and hard X-ray emission in GRB afterglows. The XEUS telescope will achieve high-energy response (up to 90 keV) employing super mirror technology whereby the inner mirrors will be coated with graded multilayers. The detectors will be implemented as part of the Wide Field Imager which also has DEPFET and CCDs to cover the soft- X-ray survey science. Solutions for the associated focal plane Hard X-ray Imaging Camera have been investigated by the XEUS Instrument Working Group and will be discussed in the present contribution.

Keywords: Hard X-ray camera, X-ray astronomy, CdTe, CdZnTe, focal plane detector, Semiconductor detectors

1. INTRODUCTION

The introduction of imaging capabilities in the hard X-ray range (10-100 keV) with the use of focusing techniques (e.g. multi-layer optics) will give access to a new observing window. Present instrumentation in this range is based either on collimated instruments or mask techniques. While imaging can be achieved with mask-based instrument, the limiting sensitivity is always dominated by the background of the entire detector, giving a typical source detection limit of about $10^{-11} \text{erg cm}^{-2} \text{s}^{-1}$. With XEUS, it is expected to achieve an area of about 2000 cm$^2$ @30 keV with a point source concentrated in a spot of 5" (HEW). For a power-law spectrum with photon index of 1.7, the source detection limit in 100 ksec (assuming a negligible background in the source region) would roughly be $F(10-40 \text{keV}) = 10^{-15} \text{erg cm}^{-2} \text{s}^{-1}$, i.e. 4 orders of magnitude lower than present instrumentation. A good continuum spectrum (i.e. about 100 cts in total) would be obtained in 100 ksec for a source giving about 20 cts in each single resolution bin, corresponding to $F(10-40 \text{keV}) = 2 \times 10^{-14} \text{erg cm}^{-2} \text{s}^{-1}$. The full spectroscopic capability of the focal plane detector (energy resolution of 1 keV @ 60 keV) would be exploited for a source giving about 20 cts in each single resolution bin, corresponding to about $F(10-40 \text{keV}) = 3 \times 10^{-13} \text{erg cm}^{-2} \text{s}^{-1}$ for a 100 ksec observation. These performances, already unique by themselves, when combined with the unprecedented capability of XEUS in the lower energy range, will open exciting prospects in several fields.

2. SCIENTIFIC CASE

2.1. The obscured Universe and AGN

Deep X-ray surveys have resolved the X-ray background around 1 keV into a population of discrete sources almost entirely composed of AGN. The energy density of the X-ray background peaks at $\sim 30$ keV, but only a fraction of this total energy density can be accounted for by the AGN population that dominates the soft X-ray

Further author information: (Send correspondence to C. Budtz-Jørgensen)
C. Budtz-Jørgensen; E-mail: carl@dsri.dk, Telephone: +4535325726
Address: DSRI, Juliane Maries Vej 30, DK-2100 Copenhagen Ø
background. On the other hand, we also know that many nearby AGN are heavily obscured and that the central engine is visible only at high energies. Models derived by adding together the X-ray spectrum of a large number of absorbed AGN at different redshifts with various column densities succeed in reproducing the spectrum of the hard X-ray background. The total energy produced by AGN may be comparable to that generated by the stellar population, with the AGN output mostly hidden by obscuring regions. The hard X-ray capability of XEUS will be crucial in clarifying this scenario. The population of sources making up the X-ray background above 10 keV should be composed of heavily absorbed objects ($N_H > 10^{24} \text{ cm}^{-2}$). From the extension of the log N-log S from lower energies, most of the XRB above 10 keV can be resolved by XEUS: in a typical 100 ksec observation, hundreds of sources should be detected in the hard X-ray band in the 15' FOV available at 30 keV. Being obscured, their optical counterparts should be extremely faint, hence the detection of Iron $K\alpha$ line could provide the only method to determine their redshift. The X-ray redshift of this population of sources could be directly derived from the spectroscopy data gathered below 10 keV with one of the NFI instruments. For the brightest ($F(10-40) > 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$) sources, high quality spectra catered by XEUS from 0.1 to 80 keV will enlighten the properties of the absorber and the central engine, up to $z=1$ for a moderately bright source ($L=10^{44} \text{ erg/s}$) and $z=3-5$ for the more luminous AGN, leading ultimately to the cosmic history of the accretion power produced in the Universe.

2.2. Non-thermal emission from clusters of galaxies

In the last years a growing evidence for non-thermal emission in Clusters of galaxies has accumulated. In hard X-rays, power-law tails dominating the thermal emission above around 10 keV have been detected by BeppoSAX in clusters like Coma, A2256 and others, with a luminosity of a few times 1043 erg/s in the 20-80 keV range (e.g. Fusco-Femiano et al., 1999). The most likely explanation is Inverse Compton scattering of the cosmic microwave background by a non thermal population of electrons, although alternative explanations have also been proposed. This population of electrons is also producing radio emission by synchrotron, in agreement with the observation of radio halos in these sources. With the imaging capability catered in hard X-rays by XEUS, it will be possible to clarify the origin of this component and understand the acceleration processes in the ICM by mapping the non-thermal emission in several clusters of galaxies, and measuring the spectrum of an hard X-ray component as faint as 1/10 of that observed in Coma up to $z=1$. The study of the evolution of the “non-thermal power” in Cluster of galaxies with redshift will be very important in clarifying the formation processes of these structures, since the acceleration processes are likely connected with the formation of shocks generated during merging.

2.3. Non-thermal emission from SNR and star forming regions and the origin of Cosmic Rays

Hard X-ray observations over the past several years initiated by ASCA and followed by RXTE, BeppoSAX and, more recently by XMM, have demonstrated the presence of non thermal X-ray emission arising from shells of young SNR such as SN1006, Cas A and RXJ1713.7-3946. This emission, a power law with energy index 2 extending to several tens of keV is attributed to synchrotron emission from electrons shock-accelerated to hundreds of TeV. The luminosity of this component in the 10-40 keV range is around $10^{35}$ erg/s. This finding is supported by the detection of TeV gamma-rays from two of these remnants. Another family of hard non-thermal X-ray sources, which are suggested by the detections of a number of galactic un-ID sources by EGRET observations, are systems composed of a SNR interacting with a nearby molecular cloud. The CANGAROO team has argued that TeV gamma-rays are produced by high energy protons via. the decay of $\pi^0$ (rather than by inverse Compton of electrons as in the cases mentioned above). Since cosmic rays are constituted primarily by protons, this evidence would mean that the production of cosmic rays in our Galaxy could be conclusively linked to SN explosions, if this process is indeed present in most SNR. Hard X-ray observations could provide important information in this respect, because the population of electrons and protons should also produce hard X-rays through bremsstrahlung with a spectrum distinctly different from that attributed to synchrotron emission from electrons. The position of the spectral break gives us a clue to discriminate between protons and electrons. Evidence of non-thermal power law emission has been found in two molecular clouds (probably associated with SNR), with a flat shape ($G=0$) consistent with that expected from bremsstrahlung of loss-flattened distribution of electrons or protons in a dense region (Uchiyama et al., 2002). With the hard X-ray capability of XEUS...
it will be possible to provide a census of the non-thermal properties of SNR up to distances far beyond the boundary of our Galaxy, reaching out to M31.

2.4. Other topics

Probing the SN explosions: Hard X-ray images in the Ti\textsuperscript{44} lines at 68 and 78 keV in SNR, recently detected by BeppoSAX will provide information about the explosion that formed them, since the amount of Ti\textsuperscript{44} synthesized depends sensitively on the explosion energy, asymmetries and mass cut. While it is expected that INTEGRAL will provide information about the total mass of the Ti\textsuperscript{44} (via the observation of the line at 1157 keV), with the imaging and sensitivity capability of XEUS it will be possible to map the distribution of Ti\textsuperscript{44} in the SNR.

The hard X-ray properties of afterglows of Gamma-ray bursts: But for the first thousands of seconds after the GRB, no information on the hard (>10 keV) emission of X-ray afterglows of GRB is available. Particularly important in this respect is the long term evolution of the x-ray spectrum at high energies. With the XEUS hard X-ray sensitivity, it will be possible to measure the hard X-ray spectral evolution for several weeks after the burst. Combined with the lower energy capability, this will provide a spectral coverage spanning three orders of magnitude in energy, i.e. the same bandwidth from optical to X-rays. The temporal and spectral evolution of the continuum will give important clues as to the fireball evolution (jet vs spherical expansion), the environment in which it expands (ISM vs wind from massive progenitor), ultimately leading to the nature of the progenitor and the energy budget of these explosions.

3. HARDWARE IMPLEMENTATION

A very high sensitivity in the 10-80 keV band will be achieved by employing a multi-layer, grazing incident hard X-ray telescope (“super mirror”) in conjunction with a hard X-ray imaging detector. Since the super mirror is able to cover the energy range from ~0.2 keV up to 60-80 keV, the focal plane detector is required to cover a very wide energy band. One idea is to combine a fully depleted X-ray imaging device (soft X-ray detector) such as an active pixel detector and a pixelated CdTe detector as already proposed for the hybrid camera of the future Japanese NeXT mission (Takahashi et al., 2000). Soft X-rays will be absorbed in the soft X-ray detector, and hard X-rays will penetrate the CCD and be absorbed in the CdTe pixelated array. Pixel electrodes are formed on the surface of CdTe and each electrode is bump-bonded to the readout electronics chip (ASIC).

A schematic design of the hard X-ray camera (HXC) is shown in Figure 1, together with the soft X-ray detection part and the shield. In order to obtain an ultimate sensitivity for both soft X-ray and hard X-ray
energy band, active shielding is important. For this, detectors should have fast timing resolution of 10 to 100 µs, such that we can veto the detectors when there is a hit in the active shield.

3.1. CdTe and CZT

The focal plane detector should have a sufficient efficiency at least up to 80 keV. Semiconductor detectors with high mass absorption coefficient seem to be the choice, since we need a fine position resolution of several 100 µm and a high energy resolution better than ΔE < 1 keV. Among the range of semiconductor detectors available for hard X-ray detection, CdTe and CZT have a privileged position, because of their high density and the high atomic number of their components, as well as a wide bandgap. Photoelectric absorption is the main process up to 300 keV for CdTe, as compared to 60 keV for Si and 150 keV for Ge. Figure 2 shows the efficiency of CdTe, Si and GaAs gas for 60 keV photon as a function of the detector thickness. Even a detector with a thickness of 0.5 mm provides a good detection efficiency for the hard X-ray region covered by the super mirror of the Xeus mission.

Thanks to the remarkable progress in the technology of producing a high quality crystal of CdTe and CZT in the 1990s, large area CdTe/CZT detectors are now available (see review by Takahashi and Watanabe, 2001). The uniform charge transport properties of the wafer are very important aspect for fabricating large area strip or pixel detectors. CdTe crystal grown by the Traveling Heater Method (THM-CdTe) would be one choice for the material, because we can obtain a highly uniform wafer as large as 2 cm x 2 cm, see Takahashi et al., (2002). Grain boundaries and a distribution of Te inclusion, which deteriorates the spectrum, are very rare in the wafer.

Figure 3 shows the spectrum taken with the CdTe diode detector produced from a single crystal of CdTe. The detector is operated at room temperature (20 °C).

Detectors based on CZT semiconductor compounds achieve equally good energy response with energy resolutions ≤ 1 keV at 60 keV, see Harrison et al., (2002), and Kuvvetli(2003). As electron-only devices, CZT detectors, patterned with small pixels, effectively mitigate the problems associated with poor hole transport observed in CZT. The so-called small pixel effect can also be utilized to achieve depth sensing capability, e.g van Pamelen et al., and Kuvvetli(2003). This technique might be used in order to reduce the detector background. It is, however, a drawback that the production yield of large (≥ 1 cm²) uniform single CZT crystals is low.
3.2. Pixel Detector

The current goal for the CdTe or CZT detector to be used in the HXC is the pixel detector with both a fine position resolution of 200 μm and a high energy resolution better than 1 keV (FWHM) in the energy range from 5 keV to 80 keV. In order to cover the field of view of the telescope, the detector should have an area of 16 cm². If the maximum energy obtained by the super mirror is up to 80 keV, the detector thickness of 0.5 - 1 mm is enough. With this thickness, we can apply sufficient bias voltage to collect the full charge produced in the device. Full charge collection is very important to reduce low energy tail often seen in the thick CdTe and CZT detectors. Fast timing of a few μs will be required for the active shielding, which would be necessary to achieve a low background environment in space.

To realize fine pitch CdTe and/or CdZnTe pixel detectors, a readout system with more than 10,000 independent channels will be the key technology. A simple and robust connection technology needs to be established, because high compression and/or high ambient temperature would damage the CdTe and CdZnTe crystal. Figure 4 shows the radiographic image obtained with fine pixel detectors developed under the collaboration between ISAS and Bonn University. The size of the pixels is 200 μm x 200 μm. They are directly bump bonded to a two-dimensional photon counting ASIC (MPEC2) by using newly developed gold-stud bump bonding technology. The development of the low noise ASIC for pixel detectors by using deep sub-micron CMOS technology are now underway. The requirement for the power consumption is 200 μW per pixel.

As shown in Figure 6, four detectors, each with an area of 2 cm x 2 cm, will be tiled to obtain a total area of 4cm x 4 cm. 12 ASICs will be mounted underneath the CdTe detector to process the signal.

Schematic pictures for the HXC are shown in Figure 5 and Figure 6. Signals from the individual pixel electrode formed on the surface of the CdTe wafer is fed into the readout circuit built in the ASIC. The area of the circuit is same as the pixel size of the CdTe detector. Each circuit consists of CSA, shaping amplifier, comparator, and sample/hold. The trigger is generated by the OR signal made from outputs of comparators for all channels.

In order to achieve high sensitivity in the hard X-ray region, low background environment is important. As shown in Figure 5, we propose to use Silicon Strip Detectors (SSD) for the active shield. Silicon is low Z material, and therefore activated lines do not contaminate to the soft X-ray detector. In Figure 5, additional BGO shield
Figure 4. Radiographic image of a toothed wheel obtained with a CdTe pixel detector developed under collaboration of ISAS and Bonn University. The size of the pixels is $200 \mu m \times 200 \mu m$. 60 keV line from $^{241}\text{Am}$ is used to take an image.

Figure 5. Schematic diagram of the HXC camera head.
Figure 6. Schematic Diagram of the CdTe pixel detector for the HXC. Four detectors, each with an area of 2 cm x 2 cm, will be tiled to obtain a total area of 4 cm x 4 cm. 12 ASICs will be mounted underneath the CdTe detector to process the signals.

Table 1. Characteristics of the HXC

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel size</td>
<td>200 µm</td>
</tr>
<tr>
<td>Minimum threshold</td>
<td>3-5 keV</td>
</tr>
<tr>
<td>Max Energy</td>
<td>80 keV</td>
</tr>
<tr>
<td>Energy Resolution (FWHM)</td>
<td>0.5 - 1 keV</td>
</tr>
<tr>
<td>Operating Condition</td>
<td>0 - 20°C</td>
</tr>
<tr>
<td>Average Count rate</td>
<td>500 cnts/s for the entire array</td>
</tr>
<tr>
<td>Peak Count Rate</td>
<td>100 cnts/s/pixel</td>
</tr>
<tr>
<td>Time Resolution</td>
<td>10 µs</td>
</tr>
<tr>
<td>Power</td>
<td>&lt;200 µW / pixel</td>
</tr>
</tbody>
</table>

surrounds the SSD and CdTe pixel. We need to study more how K-escapes and L-escapes affect the background for both the HXC and WFCI.

If high timing resolution and high energy resolution can be achieved for the soft X-ray detector, it will allow us to use the combination of the soft X-ray detector and the hard X-ray detector as a polarization detector through Compton scattering above 30 keV.

4. CONCLUSIONS

The envisaged augmentation of the XEUS telescope with a Super Mirror in conjunction with a Hard X-ray Camera will boost the sensitivity in the hard X-ray band (10-100 keV) by several orders of magnitude compared to those of present coded mask instruments. This will open exciting prospects in several fields, e.g.: highly obscured AGNs, non-thermal emissions from SNRs, AGNs and clusters of galaxies, nuclear line emission from SNRs and hard X-ray emission in GRB afterglows.

The presented HXC will be based on CdTe or CZT semiconductor compound detectors coupled to multi pixel (ASIC) readouts. The CdTe/CZT technologies have made substantial progress and detectors with characteristics
close the XEUS HXC requirements have already been realized. Readout ASICs are under development at several places and will reach the HXC specifications in the foreseeable future.

The presented HXC active shielding requires still further analysis and optimization. It is a concern that K and L escape lines from the shield will produce background in the XEUS soft X-ray instrumentation (WFI) as well as the HXC.

The complex baffling system which is required for all the XEUS focal instruments is presently under investigation.

REFERENCES