BROAD X-RAY SPECTRAL BAND STUDIES WITH ASTROSAT

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ABSTRACT

Astrosat is a broad spectral band Indian Astronomy satellite covering 0.5 - 100 keV X-rat region as well as ultraviolet and visible bands to carry out multi-wavelength observations of a variety of X-ray sources. This is achieved by means of 3 co-aligned X-ray astronomy instruments and one UV imaging instrument. This mission is aimed at high time resolution X-ray timing studies, low and medium resolution X-ray imaging and spectral measurements and simultaneous imaging and photometric observations in the UV and optical bands for different classes of X-ray and UV bright objects. Astrosat is well suited for studies of rapid variability like pulsations, kHz QPOs, Sporadic bursts etc. in X-ray binaries ,continuum Xray spectral measurements of binaries, AGNs ,Cluster of galaxies etc. and also construct energy spectra of sources over five decades in energy from simultaneous measurements. It will have superior sensitivity in the hard X-ray band for detection of of cyclotron lines, measurements of non-thermal components in the spectra of black hole sources, supernova remnants, Cluster of galaxies etc. and also extend studies of QPOs to hard X-ray region. The Astrosat is planned for launch using Indian PSLV in a near equatorial orbit of 600 km altitude in 2007/2008. Characteristics of the instruments are briefly presented and science goals of the mission are highlighted baed on simulations.

1. INTRODUCTION

To understand the nature of cosmic sources, their radiation processes and environment, it is necessary to measure their emission over the entire electro- magnetic spectrum. Since intensity of several classes of cosmic sources varies with time, simultaneous observations in different wave-bands are required to construct their energy spectra as well as measure their variability. Most of the space observatories are designes for observations ina particular band e.g. X-ray, UV etc. Therefore, multiwavelength studies usually have to be made from coordinated observations with different satellites (Edelson et al.1996).The most efficient and effective way of multiwavelength studies is to have a dedicated satellite mission which will carry several co-aligned instruments covering the desired spectral bands. The proposal for Astrosat as an Indian multiwavelength Astronomy Satellite has been conceived to meet the long felt need for such a mission. The uniqueness of Astrosat lies in its wide spectral coverage extending over visible, ultraviolet, soft x-ray and hard x-ray regions with capability to observe a target source over a wide band with 4 co-aligned instruments simultaneously.

Astrosat is a collaborative effort of several Indian institutions, Canadian Space Agency and Univercity of Leicester, UK. These include Tata Institute of Fundamental Research (TIFR), ISRO Satellite Center (ISAC), Indian Institute of Astrophysics (IIA), Raman Research Institute (RRI), Inter-University Center for Astronomy and Astrophysics (IUCAA) and Physical Research Laboratory (PRL), all of which are involved in the development of hardware for this mission. Besides, several centers of Indian Space Research Organization (ISRO) are involved in the design and fabrication of various components and sub-systems of the 5 instruments. Several other Indian institutions will be involved in the development of science analysis software.

2. ASTROSAT SCIENCE GOALS

The Astrosat mission has been conceived with the principal objectives of (a). Multiwavelength studies of cosmic sources over a wide spectral band extending over low energy X-rays (0.3 - 8 keV), high energy X-rays (10-100 keV), UV (120 - 300 nm) and visible bands from simultaneous observations with co-aligned instruments. (b). Measure correlated intensity variations to investigate the origin and mechanism of the emission of radiation in different spectral bands. (c). X-ray studies of periodic (pulsations, binary light curves, QPOs etc) and aperiodic (flaring activity, bursts, flickering and other chaotic variations) variability by high time resolution (10 μ sec) photometry in 0.3-100 keV band. Rapid variability studies, high and low frequency QPOs, kHz QPOs in soft and hard X-ray bands, probe astrophysical processes closest to the central source. (d). Broad band X-ray spectroscopy

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of X-ray binaries, Supernova remnants (SNRs), Active Galactic Nuclei (AGNs) etc with moderate energy resolution (E/ Δ E ~ 30-50) X-ray CCD in Soft X-ray Telescope (SXT), low resolution (E/ Δ E ~ 6-10) LAXPCs covering 3-80 keV and CZT detector array with E/ ΔE \sim 10 to 20 in 10-100 keV. Astrosat is particularly well suited for investigating the non-thermal spectral component due to very large effective area above 20 keV. (e). Studies of cyclotron lines in the spectra of the X-ray pulsars to measure magnetic fields of neutron stars. (f). UV Studies of a variety of galactic sources including active stars, cataclysmic variables (CVs), X-ray binaries, SNRs etc. (g). Ultraviolet imaging studies of nearby and distant galaxies and AGNs to probe their structure, spectral energy distribution, studies of starburst activity and ionized gas.

3. ASTROSAT INSTRUMENTS

The instruments chosen for realizing the science goals of Astrosat are:

3.1. Large Area X-ray Proportional Counters (LAXPCs):

LAXPC will be used for the timing and spectral studies covering broad energy band (3-80keV). This is a cluster of 3 identical co-aligned proportional counters in a multi-layer geometry with 1° X 1° field of view (FOV). The X-ray detection volume is 15 cm deep consisting of 60 anode cells each 3.0 cm X 3.0 cm arranged in 5 layers surrounded on 3 sides with veto cells of size 1.5 cm x 1.5 cm for rejection of non-cosmic X-ray background. Each LAXPC is filled with 90% Xenon + 10% Methane at 1600 torr pressure to provide an average detection efficiency of 100% below 15 keV and \sim 50% up to 80 keV. A 25μ thick aluminized Mylar film supported against pressure by a honeycomb shape collimator serves as the X-ray entrance window. The FOV collimator is made by gluing layers of tin,copper and aluminium. The total effective area of 3 LAXPCs is about 6000 cm² below 20 keV and about 5000 cm² at 45 keV making it the largest effective area hard X-ray detector ever flown in a satellite mission (Fig.1). This will provide high sensitivity for the timing observations in the hard X-ray band.

3.2. Cadmium-Zinc-Telluride Imager (CZTI):

Medium resolution spectroscopy and low resolution imaging (0.1 degree) in 10-100 keV is achieved by CZTI. The CZT array has a geometrical area of 1024 cm² made up of 16384 pixels each 2.5 mm x 2.5 mm X 5 mm thick read out by 128 ASICs each having 128 channels. This will provide position and energy of each detected X-ray. The imaging will be realized by a coded aperture mask(CAM) of tantalum with 17° x 17° FOV placed above the CZT plane. The CZT detector will be operated



Figure 1. Effective area as a function of energy for LAXPC Instrument

in -0°C to -20°C range by passive cooling using a radiator plate of appropriate area. The CZT has superior energy resolution compared to the LAXPCs, above 40 keV with expected resolution of about 7% at 60 keV. Compton scattering produced background in the CZT will be eliminated to a great extent by using a 2.5 cm thick Caesium Iodide detector immediately below the CZT plane operated in anticoincidence mode.

3.3. Soft X-ray Imaging Telescope (SXT):

SXT will carry out moderate resolution (3') imaging, and medium resolution (E/ Δ E ~20 to 50) spectroscopy in 0.3 to 8 keV based on the use of conical foil mirrors of 2 meter focal length with X-ray CCD as the detector. The conical foil X-ray mirrors and CCD detector have been used successfully in the ASCA mission (Tanaka et al. 1994). The gold coated X-ray reflecting mirrors made by nesting 41 conical shells, have been formed by replication process similar to the one used for the Japanese Astro-E2. An open gate, frame transfer CCD of 600 x 600 pixels of $40\mu \times 40\mu$ size having an image section and a store section, developed by Leicester University (LU) for the Swift mission, will be used for the SXT. The CCD camera will be developed in collaboration with the LU group. The CCD will be cooled to about -80°C by a thermoelectric cooler coupled to a passive radiator plate. The optical bench as well as the entire SXT housing cylinder will be fabricated using CFRP. The CCD will be read out in imaging, timing and photon counting modes with maximum intensity for a point source of ~ 100 mCrab without pile up. The CCD will have an energy resolution of about 130 eV at 6 keV and an effective area of about 200 cm^2 at 2 keV dropping to 25 cm² at 6 keV. The expected count rate of SXT is about 1.4 cps per mCrab.

The Ultraviolet Imaging Telescope (UVIT): 3.4.

The UVIT instrument consists of two identical telescopes each with 38 cm aperture primary and 14 cm secondary and uses three channel plate multiplier and CCD/CMOS

based photon counting detectors. It will have angular resolution of about 2", a circular filed of 0.5°, time resolution of about 1 s and sensitivity to detect a 21 magnitude star in 1000 sec exposure in 50 nm pass band. One telescope will cover 120 -180 nm far-uv (FUV) band while the second telescope will have a dichroic beam splitter to provide two pass bands, 180-300 nm near-uv (NUV) band and the 350-650 nm visible band. In addition several filters with pass band of 10 to 50 nm centered at UV lines, will be mounted in a filter wheel in each telescope for narrow band imaging and photometry. The mirrors will be made from light weighted Zerodur with aluminium reflecting surface protected by a layer of magnesium fluoride. The telescopes will have suitable baffles above them to reduce background due to stray light. The three Photon Counting Detectors (PCDs), 2 for the 2 UV and one for the Visible channel, are being made in collaboration with the Canadian Space Agency (CSA). The CCD/CMOS frames are read out at a suitable rate to obtain the position of the photons to construct an image of the sky under observation.

3.5. Scanning X-ray Sky Monitor (SSM):

This is similar in design to that of the highly Successful All Sky Monitor (ASM) on the RXTE. It is based on the use of a one dimensional Position Sensitive Proportional Counter (PSPC) sensitive in 2-10 keV with an aluminium coded mask aperture of $6^{\circ} \times 90^{\circ}$ FOV placed above it. The SSM will consist of 3 coded mask cameras with PSPCs, mounted suitably on a boom with rotation capability to scan the sky. Each PSPC has 8 anode cells of 1.2 cm x 1.2 cm,has a 25μ thick Mylar window and will be filled with a mixture of Argon,Xenon and Methane at 800 torr. The position of the incident X-ray is measured by charge division technique to an accuracy of about one mm. The position of a source will be measured along the scan direction to an accuracy of 6' to 8' depending on the source intensity.

A summary of the characteristics of all the Astrosat instruments is given in table 1.

4. ASTROSAT MISSION DETAILS

The Astrosat will be a three axis stabilized satellite with orientation maneuvers and attitude control done by using reaction wheels and magnetic torquers which get input from 3 gyros and 2 star sensors. It will have pointing accuracy of about one arc second. A solid state recorder with 120 Gb storage capacity will be used for on board storage of data .The data will be transmitted by two carriers, once in all the visible orbits, at a rate of 105 Mb / sec. The total mass of Astrosat observatory is estimated to be 1600 kg including 868 kg mass of the scientific instruments. It will be launched in a circular orbit of about 600 km altitude with orbital inclination of 8 degree by well proven Indian Polar Satellite Launch Vehicle (PSLV)

	UVIT	LAXPC	SXT	CZTI	SSM
Detector	Photon Count- ing, CPM + CCD based UV and optical detec- tors	Multilayer Propor- tional Coun- ters	X-ray CCD (at the focal plane) of Wolter- 1 coni- cal foil mirrors	CdZnTe detector array	Position- sensitive propor- tional counter
Optics	Twin Ritchey Chretian optics with 38 cm aperture primary	Collimator	Conical foil mirrors (~Wolter- 1)	2-D coded mask	1-D coded mask
Band Width	128- 180nm uv 180- 300nm 350- 650nm	3-80 keV	0.3-8 keV	10-100 keV	2-10 keV
Effective Area (cm ²)	~25 in 120- 300nm 50 in 350- 650nm	6000 @ 5-30keV 5000 @ 50keV	125 @ 0.5keV, 200 @ 1-2keV, 25 @ 6keV	500 (E≤10 keV)	~40 @ 2keV 90 @ 5keV (Xe gas)
Field of View	0.50° di- ameter	1º x 1º	0.35° (FWHM)	17° x 17°	6° x 90°
Energy Reso- lution (FWHM)	≤100 nm (filters dep.)	10% @ 22 keV	~2% - 3% @ 6keV	5% @ 60keV	19% @ 6keV
Angular Reso- lution	2 arcsec	~1-5 arcmin (scan mode only)	3 arcmin (HPD)	8 arcmin	\sim 5-10 arcmin
Time Reso- lution	1 S	10µsec	2.6 s, 0.3 s, 1 ms	1 ms	1 ms
Sensitivit (Obs.Tim in ks)	y20 mag- enitude $(4\sigma)in$ 50 nm band	0.1 mCrab (3σ) (1K)	$\frac{10}{\text{mCrab}(5\sigma)}$ (10 K)	0.5) mCrab (5 σ) (10K)	$ \begin{array}{c} \sim 30 \\ \text{mCrab} \\ (3\sigma) \\ (0.3 \text{ K}) \end{array} $
Total Mass (KG)	290	390	90	50	48



Fig. 2. Simulated wide band X-ray spectrum from the Coma cluster

Figure 2. Simulated wide band X-ray spectrum from the Coma cluster

from Shriharikota range in India in 2007/2008. The Astrosat will have a minimum mission life of 5 years.

5. EXPECTED SCIENCE FROM ASTROSAT:

Multiwavelength studies will be a unique capability of Astrosat that will improve understanding of the radiation processes and the environment in the vicinity of the central compact objects in the AGNs. Observations of binaries with neutron star, black hole or white dwarf as Xray source will lead to understanding of the nature, environment, site and geometry of X-ray and UV emission of these objects. Variability studies over a wide spectral and time domain are crucial for probing the nature of the sources and the cause of variability (van dar Klis 2000). Detection and detailed studies of kHz QPOs in hard X-rays is an almost unexplored area that is important to probe the accretion flows closest to the compact source. One will be able to successfully search QPOs from the X-ray sources with LAXPC in the kHz range if the source intensity rises above 50 mCrab. The X-ray spectral measurements of the continuum and lines in 0.5-100 keV interval from simultaneous observations will reveal origin of the different components of the spectra and parameters of the radiation processes.

Simulated wide band X-ray spectra of Coma Cluster of galaxies are shown in Figure 2 for the SXT, LAXPC and the CZT.The X-ray spectrum of Coma cluster measured by Rephaeli et al. (1999) with the RXTE was used in simulation.

With an exposure of 1 day LAXPCs will provide spectrum with good statistical significance for a 0.1 mill Crab intensity X-ray source. The CZT Imager will be able to detect a source of 0.5 milliCrab in 1000 s and obtain a good spectrum in one day of observation. The cosmic X-ray sources, that will be observed with these detectors, range from the nearby solar-mass Galactic X-ray binaries to the largest structures in the universe, the clusters of galaxies. The sensitivity of the LAXPCs and the CZT array for measurement of magnetic field of nutron stars



Fig. 3. Simulated X-ray spectrum of the pulsar 4U0115+63 for the LAXPC and CZT showing cyclotron absorption features

Figure 3. Simulated X-ray spectrum of the pulsar 4U0115+63 for the LAXPC and CZT showing cyclotron absorption features

is unmatched by any other existing experiment. Using the cyclotron line fluxes detected from the X- ray pulsar in 4U0115+63 with RXTE, a simulation of the expected signal in the LAXPC array is shown in Figure 3 along with the actual observed spectra from RXTE-PCA and BeppoSAX PDS (Heindel et al. 1999, Santangelo et al. 1999). It is obvious that the cyclotron lines will stand out very clearly in the LAXPC spectrum compared to shallow dips in the PCA and PDS spectra. Spectroscopy of hot thin collisional plasmas in galaxies, clusters of galaxies, supernova remnants and stellar coronae, and photoionized matter in accreting white dwarfs, neutron stars, black-holes and AGNs would be carried out with SXT. With energy resolution that is 10 to 50 times better than that of the proportional counters, SXT will separate the line emission and absorption components from the continuum in all known varieties of objects.

The imaging UVIT observations with ~ 2 arc sec angular resolution will measure the morphology and energy distribution of galaxies in the local region i.e. at the present epoch and compare them with those at the high red shift. The UVIT will detect first burst of star formation in low surface brightness blue dwarf galaxies from morphological studies by deep imaging observations. It will also study star bursts in distant galaxies and map the ionized gas in them. The UV colours will provide a measure of the properties of the dust in normal and starburst galaxies. It will map the Galactic H II regions, planetary nebulae and supernova remnants in our Galaxy well as those in the nearby galaxies in various emission lines e.g. CII (235 nm), CIII (190.9 nm), CIV (155 nm), O II (247 nm) etc. to map the elemental distribution and the physical condition of the gas. By studying early type hot OB stars in our Galaxy and their distribution in nearby galaxies one will be able to obtain the star formation histories and enrichment of gas.

The Astrosat observatory with 4 co-aligned X-ray and UV instruments and an X-ray sky monitor will be a powerful tool to probe the astrophysical processes and environment of all kinds of astronomical sources. With its broad spectral coverage in the X-ray band and simultaneous UV and visible observation capability, it is expected to bring about a qualitative change in the multiwavelength astronomy.

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THE XMM-NEWTON SLEW SURVEY: A WIDE-ANGLE SURVEY IN THE 0.2 – 12 KEV BAND

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ABSTRACT

The scientific data collected during slews of the XMM-Newton satellite are used to construct a slew survey catalogue. This comprises of the order of 4000 sources detected in the EPIC-pn $0.2 - 12 \,\text{keV}$ band with exposures of less than 15 s and a sky coverage of about 6300square degrees (source density ~ 0.65 per square degree). Below 2 keV the sensitivity limit is comparable to the ROSAT PSPC All-Sky Survey and the XMM-Newton slew survey offers long-term variablity studies. Above 2 keV the survey will be a factor of 10 more sensitive than all previous all sky X-ray surveys. The slew survey is almost complementary to the serendipitous survey compiled from pointed XMM-Newton observations. It is aimed to release the first source catalogue by the end of 2005. Later slew observations and detections will continuously be added. This paper discusses the XMM-Newton slew survey also in a historical context.

Key words: X-rays; XMM-Newton; EPIC-pn; slew; survey; catalogues.

1. INTRODUCTION

The development of new space instrumentation for X-ray astronomical applications aims towards higher collecting areas, higher spatial resolution, and higher spectral resolution. This is related to smaller and smaller fields of view. Observations like *Deep Surveys* (e.g. in the directions of the Lockman Hole, the Hubble Deep Field North, etc.) – with exposures of the order of 10^6 s until they reach the confusion limit – can help to study the faint end of luminosity functions and thus to analyse the most abundant sources in the Universe.

All-Sky Surveys, on the other hand, with shallow exposures but a large sky coverage, are the proper database to study rare objects, with a small surface number density, and also the bright end of luminosity functions. As an example, the ROSAT All-Sky Survey (RASS) with its *Bright Source Catalogue* with 18811 sources in the 0.1 - 2.4 keV band (Voges et al. 1999a,b) exceeded any previous large-area X-ray survey in terms of sensitivity and number of new sources.



Figure 1. Sky distribution of 465 EPIC-pn slews (FF, eFF, LW modes) in ecliptic coordinates. Note that slews are performed close to great circles due to solar angle constraints.

Slew Surveys play an intermediate role between specially designed all-sky programs and dedicated pointed observations. The *Einstein* IPC slew survey (Elvis et al., 1992) covered half of the sky in the 0.5 - 3.5 keV band with a sensitivity of about 3×10^{-12} erg cm⁻² s⁻¹ (0.1 IPC cts/s⁻¹) and the resulting catalogue contained 819 sources. 15% of those had no counterpart in the (slightly softer) RASS (Schachter et al., 1993). All-sky survey extensions into (and beyond) this harder energy range have been proposed like ABRIXAS as a path-finder for XMM-*Newton* (Trümper et al., 1998) and ROSITA (Predehl et al., 2003), but the first failed and the latter is not yet approved.

XMM-*Newton* with its superior collecting area would also be an ideal mission for serendipitous science as already in short exposures during slews enough photons could be detected for a classification of the sources (X-ray colours, extents, etc.). 5 years before the launch the potential of such a slew survey was outlined (Lumb, 1995). Pre-launch predictions and feasibility studies, however, were based on assumptions on the slew rate of smaller than 20° per hour (Jones, 1998; Lumb, 1998; Jones & Lumb, 1998); the actual slew rate of 90° per hour reduces the typical number of photons per source but increases also the sky coverage (faster slew gives more possible observations and thus more slews).

2. OBSERVING STRATEGY

The scientific payload of the XMM-*Newton* satellite (Jansen et al., 2001) consists of three highly nested Wolter type-I X-ray telescopes (Aschenbach et al., 2000) and an Optical Monitor sensitive in the optical and UV to allow simultaneous observations in a broad energy band up to about 12 keV. The corresponding X-ray instrumentation is made up of the Reflection Grating Spectrometer (RGS). which shares two of the three telescopes with EPIC-MOS detectors (Turner et al., 2001) while behind the third telescope the EPIC-pn camera (Strüder et al., 2001) receives the full intensity. In the context of the XMM-*Newton* Slew Survey only the imaging EPIC camera is relevant.

The XMM-Newton mission planning tries to reduce overheads such as long slews from one pointed observation to another. These slew manoeuvres between two observations and before and after perigee passages are executed with the help of reaction wheels. In the early phase of the mission during slews the instruments were put into an IDLE setup, i.e. they were not completely switched off but did not collect data (except for a few exposures with calibration filter set-up). From revolution 314 (26 August 2001) onwards for slews lasting an hour or longer the EPIC instruments were set into OBSERVATION mode with the same observation submode as the last exposure before, and the filter wheel moved into Medium filter position. In particular, for EPIC-pn no new offset maps were computed and no changes to the uploaded bad pixel maps were applied. Figure 1 illustrates the slew paths in ecliptic coordinates. Due to solar angle constraints slews are performed close to great circles.

The slew rate ρ in the open slew phase is about 90° per hour. As the time resolution and thus the attitude reconstruction of CCD events is limited by the frame time $t_{\rm ft}$, any image of an X-ray source scanned during a slew is distorted along slew direction by $\rho \times t_{\rm ft}$.

Table 1 lists the frame times for all EPIC imaging modes where all CCDs (7 for EPIC-MOS and 12 for EPICpn) are operational and in the same mode (note, that for EPIC-MOS the outer 6 CCDs are always operated in *Full Frame* mode). From this compilation it is clear that the EPIC-pn *Full Frame* (FF), *Extended Full Frame* (eFF), and the *Large Window* (LW) modes are acceptable in terms of distortion of the point spread function while



Figure 2. Example of a bright source found in "pilot-0" study. Top: detector image, LW mode. Middle: light curves of each CCD in same orientation as above (5 s time bins, 0.2 - 12 keV); the source can clearly be identified as strong increase in CCDs 7 and 4. Bottom: source spectrum.



Figure 3. Distribution of EPIC-pn count rates in the 7.5 - 12 keV band, for the total FOV averaged over a complete slew. Left: differential distribution for FF (solid), eFF (dotted), and LW (dashed) modes. Right: the corresponding cumulative distributions. The vertical line indicates the threshold of $5.5 \text{ counts s}^{-1}$ as our selection of "low-background slews", discarding about 25% of the slews as "high-background". Note, that the LW mode has only about half the FOV of FF and eFF modes.

Table 1. "Large-scale" EPIC imaging observation modes, frame times $t_{\rm ft}$, and distortion of the point spread function assuming a slew rate of $\rho = 90 \, {\rm arcsec} \, {\rm s}^{-1}$. For details see text.

Mode	Frame time	Slew distortion
111040	[0]	[arcsec]
	[9]	[alesee]
MOS FF	2.6	234
pn FF	0.0734	6.6
pn eFF	0.1992	17.9
pn LW	0.0477	4.3

the EPIC-MOS FF mode distributes the source photons over a streak of about 4 arcmin during one readout cycle. Combined with the lower effective area of EPIC-MOS the background per detection cell would be too high to add significant value to the EPIC-pn slew data. Therefore since revolution 918 (12 December 2004) EPIC-MOS is operated during slews with the filter wheel moved to Cal-Closed position (see also Harbarth et al., 2005). The EPIC-pn LW mode is integrating only in the inner half of the CCD area, the field-of-view (FOV) is thus reduced by a factor of 2. The EPIC-pn Small Window (SW) mode with a frame time of 5.67 ms is only integrating in about 1/3 of the target CCD, i.e. only about 3% of the FOV, and was thus not used by us in the compilation of the slew survey source catalogue (nevertheless, bright sources can still be detected in EPIC-pn SW mode slews).

As the EPIC FOV is about 30 arcmin in diameter, the exposures of slew sources reach values of up to 15 s, depending on how central the source passed through the FOV. For comparison, the ROSAT PSPC had a 114 arcmin diameter FOV.

3. PROCESSING STRATEGY

Similarly to the *Observation Data Files* (ODFs) for pointed observations there have been created *Slew Data Files* (SDFs) with the same files and structure for slews not completely performed in IDLE setup. These SDFs have been ingested into the *XMM*-*Newton Science Archive* (XSA). The current public SAS (xmmsas-6.5.0) is able to deal also correctly with SDFs (i.e. event file creation, attitude determination, exposure map computation, source detection).

3.1. Pilot-0 study

As already mentioned above XMM-*Newton* slew observations started only in August 2001. The collected data were not immediately intended for scientific use but rather for background studies and blank sky analysis. In early 2004 the scientific value beyond a pure calibration aspect was queried. In a very first pilot study ("pilot-0") all available SDFs were processed with the standard SAS. Besides attitude related issues no problems occurred.

Special diagnostic products beyond the standard pipeline processing like detector maps in several bands and light curves of individual CCDs were constructed. A robust source search was performed on the basis of these light curves; a source was identified by its characteristic sequential variation of the rate in a number of CCDs. The attitude and thus the sky position was added later using the time information. It was shown that in all EPIC-pn imaging modes (FF, eFF, LW, and SW) sources can be detected and related to other catalogued objects.

For all SDFs background lightcurves and average rates in 6 bands for the total FOV were computed. The



XMM-Newton pointed observations





XMM-Newton slew sources in RASS



Figure 4. Aitoff projections in galactic coordinates with galactic center in image center and increasing longitude to the left. From top to bottom: RASS image for comparison (see Freyberg & Egger, 1999, and references therein). Location of all XMM-Newton pointed observations. Location of all slew survey sources (detected in the broad band); note the different spatial distribution. Location of all slew survey sources with a counterpart detected in the RASS.



Figure 5. Comparison of RASS (0.1-2.4 keV) and XMM-Newton (0.2-2.0 keV) count rates for slew sources with RASS counterpart

distribution of these rates for the highest band chosen (7.5 - 12 keV) is shown in Fig.3. The left panel contains the differential distribution for FF (solid), eFF (dotted), and LW (dashed) modes, the right panel the corresponding cumulative distributions. The vertical line indicates the threshold of 5.5 counts s⁻¹ as our selection of "lowbackground slews", discarding about 25% of the slews as "high-background". Note, that the LW mode has only about half the FOV of the FF and eFF modes and that therefore the count rates are lower by a factor of about 2.

3.2. Pilot-1 study

In a following study ("pilot-1") a number of slews in FF mode were analysed to verify effects of optical loading and to determine the best settings for image creation, energy bands, and source detection via standard SAS tasks (Read et al., 2005; Saxton et al., 2005). As the tangential plane projection is not valid anymore over the whole slew, it was split into event files of 1 square degree size and resulting sub-images were used for source detection. Sub-images with exposures of > 35 s (i.e. close to the end of the slew) were discarded from the pipeline. It was concluded to use slew data in FF, eFF, and LW modes, and to drop SW mode exposures from the slew survey catalogue processing.

3.3. Pilot-2 study

Three long low-background slews (one in FF, eFF, and LW modes, close-by in time) were specifically analysed to identify any mode-dependent features in the source detection pipeline and whether a common scheme could be applied to all EPIC-pn slew data. Aspects of this pipeline have been described in detail by Read et al. (2005) and Saxton et al. (2005).

3.4. Current scheme

From the abovementioned pilot studies the following processing scheme for SDFs was set up (see also Esquej et al., 2005):

- produce event files down to 100 eV (to be able to later identify optical loading, detector flashes etc.)
- select only FF, eFF, and LW mode slew exposures
- discard slews with average rate in 7.5 12 keV band exceeding 5.5 counts s⁻¹
- construct images and exposure maps in 3 bands: soft ("RASS") band 0.2 - 2.0 keV, hard ("beyond RASS") band 2 - 12 keV, total band 0.2 - 12 keV. Note, that in the range 0.2-0.5 keV only single pixel events are used (PATTERN==0) and above 0.5 keV also double pixel events (PATTERN.1e.4), and discard subimages with exposures > 35 s.

4. THE CATALOGUE: XMMSL1

The XMM-*Newton* Slew Survey catalogue XMMSL1 will consist of the order of 4000 sources detected in the total band (0.2-12 keV), about 2700 in the soft and about 800 in the hard bands alone, respectively. After flagging and removal of spurious sources (e.g., due to detector artifacts, optical loading, software) – which will reduce the figures mentioned above – the catalogue is planned to be released by the end of 2005 (Esquej et al., 2005).

4.1. Quality control

Quality control is a very important issue to ensure valuable scientific exploitation, and started already with the event file creation. The verbosity=5 log file of the task epchain was inspected for messages indicating possible unusual features in detector performance or data flow. The special data products described in Sect.3.1 were very useful for sanity checks. Searches for optical loading and detector artifact cases were performed below the actual slew survey limit (0.2 keV).

An extensive cross-correlation of XMM-*Newton* slew sources with various other X-ray and optical catalogues was performed: faint detections without such counterparts have a higher probability of being spurious. Figure 4 shows the distribution of XMM-*Newton* pointed observations, of slew sources, and of slew sources with a detection in the RASS. In Fig.5 we show the relation of soft band slew source rates with RASS rates, where a general correlation is observed ("XMM = $10 \times RASS$ ") with scatter due to different instrument responses in the energy bands, and also due to long-term variability, but may also point towards residual uncertainties due to optical loading or event pattern pile-up. We have also checked the slew survey sources that have *no* counterpart in the RASS and have determined upper limits for the detection to identify further candidates for visual inspection of spurious sources.

The slew survey is almost complementary to serendipitous surveys compiled from pointed XMM-*Newton* observations (see, e.g., Barcons et al., 2002, for the AXIS programme). This is mainly due to a selection bias because the sky portion observed in the pointing at the start and at the end of a slew is not part of the slew survey. It did, however, happen that a slew passes over a field that is part of the pointed programme at a different phase. These cases can also be used for variability studies.



Figure 6. Sensitivity limits for various X-ray surveys.

4.2. Survey sensitivities

The short exposure times in the XMM-Newton slew survey are partly compensated by the superior collecting area of the X-ray telescopes. Below 2 keV the sensitivity limit of $6(4.5)10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$ (for detection likelihoods of 10 and 8, respectively) is comparable to the ROSAT PSPC All-Sky Survey, and the XMM-Newton slew survey offers long-term variablity studies. Above 2 keV the survey will be a factor of 2.5 more sensitive $(4(3)10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2})$ than the RXTE survey (Revnivtsev et al., 2004) – which has a positional accuracy of only $\sim 1^{\circ}$ – and a factor of 10 compared to other (spatially resolved) large-area X-ray surveys (Exosat, HEAO-1). Figure 6 compares sensitivity limits of previous surveys with the current XMM-Newton slew survey.

The RASS showed large exposure inhomogeneities due to the survey design: all slews scanned over the ecliptic poles leading to a significantly higher exposure there than in the ecliptic plane. The XMM-*Newton* slew survey is not that strongly biased to the ecliptic poles: Fig.1 shows instead a wide scatter of slew paths, and due to the significantly smaller FOV (factor ~ 14) only a number of crossings of two slew paths and very occasionally of three slew paths (there are few slew point sources that have been detected in three different slews).

When constructing luminosity functions from slew survey catalogues one has to keep in mind selection effects. As slew paths start and end just next to targets of pointed observations, these preferentially brighter sources are included in the slew survey with lower probability: there is a small bias against bright sources. Including the target area would turn the bias into an overabundance of brighter sources.

Unlike in the RASS where each part of the sky was scanned multiple times (survey rate in the ecliptic plane ~ 4 arcmin per orbit with a FOV of 114 arcmin diameter) the exposure strongly depends on the off-axis angle in the XMM-*Newton* slew. The XMM-*Newton* survey sensitivity is therefore strongly inhomogeneous perpendicular to the slew direction (rather than perpendicular to the ecliptic plane).

5. CONCLUSIONS AND OUTLOOK

It has been shown that the XMM-*Newton* EPIC-pn data collected during slews represent an important scientific database. The catalogue currently under construction will provide a complement to catalogues compiled from pointed observations (1XMM, 2XMM). Moreover, not only point sources but also extended sources had been detected in the slew survey (Lazaro et al., 2005). While supernova remnants are most likely already detected in the RASS, harder sources like clusters of galaxies may be new extended objects originating from the slew survey.

In further versions of the slew survey catalogue it is planned to recover part of the slews that were disregarded due to high background by selecting periods of low background (using good time intervals similar to pointed observations). The slew sky coverage will increase and therefore serendipitous overlaps with pointed observations and with other slew paths will increase as well. This will greatly enhance the possibility of time variability studies.

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THE VIRTUAL OBSERVATORIES: A MAJOR NEW FACILITY FOR X-RAY ASTRONOMY

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ABSTRACT

We describe how the Virtual Observatory (VO) projects in Europe, the USA, Japan, and elsewhere are meeting the challenge of providing simple and efficient access to data, from the world's observational facilities, analysis tools and computational resources.

We note the pan European Euro-VO project, and it's technological development arm - the VOTECH project (see http://www.eurovotech.org), with a focus on how it is designing the framework for mass scale access to not only major X-ray facilities now such as Chandra and XMM-Newton, but also to the large data from new facilities such as VISTA, ELTs, ALMA.

Science drivers from the X-ray research community are helping shape the development of the VO, with their requirements on access to both X-ray and supporting large multi-wavelength data sets, often coupled with comparison to theoretical simulations (e.g. in the study of galaxy clusters). We note relevant capabilities currently available, including science services from the UK AstroGrid project Future services, such as those tuned to generate 'observational' xray maps of gas in clusters, on demand from a range of input simulations will be outlined.

We give a specific usage demonstration of the AstroGrid system in mining X-ray and optical/IR data in the search for high redshift galaxies. We note how major missions and research consortia can be the first to benefit from the use of newly emerging VO systems.

Key words: Virtual Observatories, Distributed computing, X-ray astronomy.

1. INTRODUCTION

Astronomy is currently a golden age, with an explosion in the rate of new discoveries. These have been fueled by the availability of high quality observations of the cosmos, from a range of major new facilities which together have opened up the sky at all wavelengths, from radio, through gamma ray. Key examples include the Hubble Space Telescope, the European Southern Observatory's (ESO) VLTs, the Keck Telescope, the VLA, WMAP, and recently Spitzer and Swift. The view of the X-ray Universe has been revolutionised with the advent of the Chandra and XMM-Newton telescopes.

Supporting these facilities, has been the systematic surveying of the whole sky at a number of wavelengths, e.g. 2MASS, the Sloan Digital Sky Survey (SDSS), The NRAO VLA Sky Survey. Additionally our understanding of the observed Universe is aided by comparison with increasingly sophisticated and physically accurate simulations (e.g. the Hubble Volume Simulations — http://www.mpa-garching.mpg.de/Virgo/.

Taken together, these data resources have enabled major new scientific break throughs across a wide range of areas from study of the Universe at the largest scales (e.g. analysis of the CMB, supernovae, and galaxy clustering to determine the cosmological parameters).

However, the observational facilities that we now possess, and plan to construct (e.g. ALMA, ELT's, XEUS) present astronomy with a range of challenges. There is more data (at the peta scale), more complex data (objects can routinely described by many hundreds of parameters), and data from more multiple sources. Further, there is increasing pressure to ensure maximum access to data from these high value facilities, and to allow maximum re-use of their data, to allow the extraction of the maximum amount of science.

This is the challenge which the Virtual Observatory (VO) initiatives are responding to. Thus, AstroGrid (UK), NVO (USA), Euro-VO (Europe) and others are aiming to provide simple and efficient access to reduced data products from the world's observational facilities (and indeed major theoretical simulations), through standardised interfaces, and with the provision of a wide range of pow-

erful tools and algorithms to enable the analysis of the data. This will facilitate and speed the creation of new science by allowing simpler and more powerful access to data and applications.

Here we briefly describe the specific example of Astro-Grid and the Euro-VO, and how already they are providing services and capabilities of relevance to the X-ray astronomy community.

2. EXEMPLAR SCIENCE FOR THE VO

As noted in the introduction, science drivers are shaping the development processes of the VO initiatives. Many of the science cases developed by science teams advising the VO projects include aspects requiring access to a variety of high-energy (X-ray, Gamma-ray) data resources. An example is an AstroGrid case, where the integration of data and tools to allow for the rapid follow up of SWIFT (Gehrels et al., 2004) based gamma ray alerts. Fig. 1 shows diagrammatically the data flows and processes involved, where data includes that captured rapidly, or that taken over longer time intervals monitoring fading sources.

3. BUILDING THE VIRTUAL OBSERVATORY

The creation of the worldwide global observatory framework involves the formation of an international partnership to agree vital interoperability standards. VO projects then build implementations adhering to these standards, taking advantage of newly emerging distributed computing technologies and fast networks.

3.1. The International Virtual Observatory Alliance

As described in subsequent sections, national and regional VO implementations, ensure that applications and services are developed which meet the prioritised science demands of their local communities.

The major VO projects recognised, however, that, at the low level, the various implementations would have to inter-operate. Thus a data resource published through the UK's AstroGrid should be accessible to the Euro-VO, the NVO and so forth. And likewise, resources and applications published in the the USA, Europe, should be discoverable and accessible to a user working through AstroGrid. This spurred the formation of theInternational Virtual Observatory Alliance¹ (IVOA).

Scientific and technical representatives from the global VO projects are thus agreeing these interoperability standards — covering areas such as 'registries' (the index of resources), content descriptors (the astronomy dictionary to describe data), data models (providing described mechanisms to access astronomical data), data access, VO query language (one query language to enable querying of heterogeneous databases, registries, files, etc), and additional areas such as authorisation protocols. By adhering to the agreed IVOA interoperability standards in creating their VO systems, the user of one - such as AstroGrid - gains full access to the resources of the others.

An analysis of a standard VO architecture has been undertaken by the IVOA (Williams et al., 2004), giving an idea of the technical complexity underpinning any VO system. The various IVOA working groups maintain details of their activities on the IVOA wiki pages linked from http://www.ivoa.net/twiki/bin/view/IVOA/WebHome

3.2. The European Virtual Observatory

A number of partners (ESO, CDS-Strasbourg, Astro-Grid, Jodrell Bank Observatory, and Terapix-Paris) in Europe formed the successful Astrophysical Virtual Observatory Project (AVO) see http://www.euro-vo.org. This three year (2001-2004) EU Fifth Framework study programme² produced the outline of the design for a Virtual Observatory in Europe. A key success of the AVO was the production of the AVO Science Reference Mission (SRM) document, which lays out a set of exemplar science cases which will benefit from, and in many cases require use of, VO capabilities, and thus impact on the design of the VO. The AVO SRM was produced by the AVO Science Working Group and is available online at www.euro-vo.org/internal/Avo/AvoSRM/srm.pdf

With the completion of the AVO project, a more ambitious European Virtual Observatory (http://www.eurovo.org Euro-VO) initiative is underway. This is composed of a range of European consortia representing major astronomical resource providers: ESO, ESA, Astro-Grid (UK), NOVA (NL), INAF (Italy), CNRS (France), LAEFF (Spain) and GAVO (Germany). It is anticipated that it will be composed of three inter operating distributed structures:

- 1. Euro-VO Facility Centre: charged with providing user support and ensuring provision of registry services
- 2. Euro-VO Data Centre Alliance: providing a focus for the interface of major resource providers to the Euro-VO
- 3. Euro-VO Technology Centre: developing the infrastructure and technical components creating the Euro-VO. This final element is now funded.

3.3. The Euro-VO: Technology Centre

The Euro-VO Technology Centre (VOTC) is currently in progress through its VO-TECH project, a EUR 6.6M ini-

¹http://www.ivoa.net

²http://www.cordis.lu/improving/infrastructure/home.htm



Figure 1. Complex work flows involved in following up Gamma Ray Burst alerts, ranging from the capture of rapid near real time earth based followup observations, through longer term monitoring of fading sources

tiative running from Jan 2005 to Dec 2007, which is carrying out feasibility studies and design work aimed at integrating new VO and distributed computing technologies into the Euro-VO. This work is closely aligned to ensure compatibility with, and input into, emerging global astronomical interoperability standards (e.g. from the International Virtual Observatory Alliance)

The VOTECH work is organised into three main strands:

- 1. Infrastructure: the VO middleware, e.g. Workflows, job execution, security, transport layer etc
- 2. New Tools: applications for the VO, e.g. Footprint, best fitting, SED builder, etc
- Resource Discovery: finding the needle in the haystack, e.g. Building ontology's, dictionaries, resource browsers, etc
- 4. Data Mining and Visualisation: mass scale analysis, Large scale compute, multi dimensional visualisation, etc

The VOTECH project, is led by AstroGrid³ in the UK, with partners: ESO, Centre National de la Recherche Scientifique (France) and the Instituto Nazionale di Astrofisica (Italy). In the wider VOTC context, ESA, through its ESAVO⁴ initiative is also working closely with the VOTECH project in developing new technologies for eventual deployment by the Euro-VO.

3.4. Other VO Initiatives

In addition to the UK and European VO initiatives described above, a number of other major VO projects exist. These include the National Virtual Observatory (NVO) (see http://www.us-vo.org in the USA, and the Japanese Virtual Observatory (JVO) see http://jvo.nao.ac.jp/. All projects are committed to ensuring that he specific services that they provide are accessible to all other VO projects. Thus to an end user, use of any one VO project service, opens up access to data resources made available by a full range of global providers.

4. ASTROGRID: THE UK'S VIRTUAL OBSER-VATORY INITIATIVE

In the UK, the AstroGrid⁵ consortium was formed and begun activities late 2001. AstroGrid is a substantial Virtual Observatory initiative funded through the UK's Particle Physics and Astronomy Research Council eScience programme. It is a consortium of eleven UK institutes and research establishments with expertise in data handling and computational science. After an initial definition and requirements analysis phase, it moved into a major development phase as described in Walton et al. (2004). The focus in 2005 and onwards is now on the

³http://www.astrogrid.org

⁴http://esavo.esa.int

⁵http://www.astrogrid.org

transition from a developmental system to a more operationally focused system, one robust and capable enough to support significant astronomer usage.

4.1. AstroGrid Releases v1.0/ v1.1

With its version 1.0 release (May 2005), AstroGrid is providing a scientifically functional Virtual Observatory (VO) implementation, a system built conforming to emerging Interoperability and Grid standards. The v1.0 release (see Walton (2005) for a fuller description) provides a number of key capabilities:

- Data Set Access: These access modules are run at each participating data provider - and are configured to allow visibility of the underlying data resources, through the AstroGrid framework. As an astronomer, one is able to perform database queries of remotely held data, utilising a standard query language (Astronomical Data Query Language, ADQL⁶, which is based on standard SQL). Alternatively they can access data held in flat files (e.g. FITS files), be they images (through a standard 'Simple Image Access Protocol' SIAP⁷, spectra, etc.
- 2. **Registry:** Each resource, be that data, application, hardware platform (e.g. CPU, disk, network), is registered to AstroGrid. This registry entry describes that resource, following the IVOA's interoperability standard. (Thus the AstroGrid registry 'harvests the registries of other VO projects, e.g. the NVO.) The registry entry is sufficiently detailed to give the system the level of knowledge about that resource, to make sensible assessments of whether it is relevant or not.
- 3. **Common Execution Architecture:** This provides a standardised framework in which any application can be run within the AstroGrid system. Each application available through the CEA is 'registered' in the **Registry**, thus is discoverable by the astronomer.
- 4. **Workflow:** this allows the ability to construct chains of processes, allowing user defined processing sequences to be carried out. This could be very simple, perhaps do a one step query of a database, or extremely complicated, with many steps. The work flow builder allows the creation of these work flows. They can be saved, and thus re-run at will.
- 5. Job Execution Scheduler: this underpins workflow. It takes the work flows submitted by the user, and sends the instructions contained therein to the various resources around the AstroGrid.
- 6. **MySpace:** This is the users own secure virtual storage made up of a number of large disk arrays hosted on the AstroGrid system. To the user, MySpace is storage space accessible by them, and available to store their work, thus data especially intermediate data, work flows, results of catalogue queries and so forth. Because MySpace servers are located on fast networks, it is ideal for storing large data sets,

⁶http://www.ivoa.net/twiki/bin/view/IVOA/IvoaVOQL

as these can be quickly uploaded from MySpace to applications that may be needed to work on them.

These services are available to the end user through either a web based portal or a client 'workbench application' (see Fig. 2). The system allows for the creation of communities (thus groups, access control and so forth), thus facilitating group working on shared data sets,

A range of client side applications configured to interface to the server services, such as the MySpace file storage system, are available to the astronomer to allow for visualisation and end stage analysis of results generated by for instance server side large scale processing jobs. These clients include: **Aladin** (Boch et al., 2004), a powerful image visualisation and catalogue access tool and **Topcat**⁸ which enables visualisation and analysis of tabular datasets.

5. USING VO TOOLS

Today, and the coming years will see an explosion in the research possibilities opened up by use of new VO tools. Already there exists a large degree of useful capability available to the astronomer. In the next sections we describe the 'science services' available through use of the AstroGrid system, and note the use of Euro-VO developed systems in the discovery of black hole populations.

5.1. AstroGrid Science Services

The initial AstroGrid release represents a paradigm shift in the way in which astronomers approach and carry out on-line data analysis and interpretation. AstroGrid's workflow based system enables many complex tasks to be undertaken.

However, it is recognised that for the new user, the basic system may require a significant learning curve before the user is able to fully exploit the system. Therefore, Astro-Grid provides a number of exemplar 'science services' which solve specific astronomical problems. These science services, provide a simple way in to the system for new users of AstroGrid to understand the operation of the system, are ready to use in science analysis, and can be adapted by the astronomer if required. The services include:

 Redshift Maker: Photometric red-shifts use broad band photometry to measure the red-shifts of galaxies rather than spectroscopy. With large imaging surveys like the Sloan Digital Sky Survey (Abazajian et al., 2003), the Isaac Newton Telescope Wide Field Survey (WFS) (McMahon et al., 2001), 2MASS (see http://www.ipac.caltech.edu/2mass), WFCAM on the United Kingdom's Infrared telescope (UKIRT),

⁷http://www.ivoa.net/Documents/latest/SIA.html

⁸http://www.star.bristol.ac.uk/ mbt/topcat/



Figure 2. Entrance into the UK AstroGrid system, via either the portal or the desktop workbench

it is practically impossible to carry out a spectroscopic campaign to determine the red-shifts of all the sources detected. Photometric red-shifts have larger uncertainties than spectroscopic red-shifts, but they are a way of determining the properties of large samples of galaxies.

The redshift maker allows the user to enter a positional search. The workflow then handles a number of tasks. The INT's WFS reduced image data files are searched for multi-colour broadband image data. If available, these images are automatically transfered from the archive and sent to an application which extracts object catalogues from each of the images. These individual catalogues are then associated to produce a master catalogue of objects with their multi-colour broadband fluxes. This catalogue is then fed into a further application which produces photometric red-shifts to each of the objects based on their colours.

The redshift maker, when run by the user through the AstroGrid Workbench, asks for a basic set of parameters, in this case the position on the sky. The workflow is then automatically run. However, the workflow is also saved to the user's MySpace area. The user can then adapt the workflow, by altering the default configuration parameters for each of the steps and applications in the workflow, and run their personalised workflow. This might allow for instance the user to adjust the detection level at which objects are extracted from the image files.

Over the coming year, this service will be ex-

panded to allow for the selection of image data from a wider collection of image survey's such as UKIDSS⁹ (Warren, 2002) - a public access infrared imaging survey). Importantly this service is ideal for use in analysis of deep X-ray data observation of galaxy clusters, when comparing with for instance deep optical and IR data to determine the distances of objects contained within those fields (e.g. Kodama et al. (2004)).

- Colour Cutter: allowing object retrieval from a number of large databases based on user selected colour cuts. The user can configure this service to access X-ray catalogues such as 1XMM/ 2XMM (XMM SSC Consortium, 2003)
- 3. **Astroscope:** returning multiple resources concerning an area on the sky, adding value and building on the NVO developed 'Datascope'¹⁰ product.
- 4. Solar Movie Maker:
 - The AstroGrid system is also of relevance to the solar physics community, through the access to solar data sets and tools. With this science service, the solar physicist can enter a time range, the service then will locate, retrieve, process and create movies from SOHO Extreme ultraviolet Imaging Telescope (EIT), SOHO Coronal Diagnostic Spectrometer (CDS) or TRACE image data over the desired time range.

⁹http://www.ukidss.org

¹⁰http://heasarc.gsfc.nasa.gov/cgi-bin/vo/datascope/init.pl

5.2. The AVO Demonstrator Products

Through the AVO programme, science cases were used to define certain VO experiments bringing together specifically developed tools for these cases. One of these was demonstrated in 2004, where various deep survey data from the GOODS (Giavalisco et al., 2004) were mined using VO tools to discover a significantly enlarged population of obscured, high luminosity Type 2 QSO's. These indicate the presence of a larger population of massive black holes and their host active galaxies than was previously predicted. This work was enabled via the access to key X-ray data including that from Chandra, with objects from that been cross matched with deep optical survey data. The work is fully described in Padovani et al. (2004).

6. CONCLUDING REMARKS

AstroGrid and other VO's are providing systems, with sufficient flexibility, to enable astronomers to carry out a wide range of astrophysical data analysis tasks in support of their research. For the X-ray community, the Virtual Observatories provide access to many major relevant Xray and related data and application resources.

We note that the initial deployment of AstroGrid release v1.0 provides the world's first fully functional integrated virtual observatory system, an emerging scientific capability with the potential equivalence of a major new observational facility. Users can find more details of how to use the AstroGrid system at http://www.astrogrid.org/release

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'PATCHING' EPIC-MOS: TEMPORAL AND SPATIAL DEPENDENCY OF THE DETECTOR RESPONSE

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ABSTRACT

XMM-Newton, having now completed over 1000 revolutions of the Earth has been an outstanding success. The EPIC-MOS CCD X-ray detectors, comprising two of the three focal plane instruments on XMM-Newton, have observed many thousands of X-ray sources, and have collected close to a billion X-ray photons. This radiation has altered the behaviour of the MOS detectors in very interesting and subtle ways, and these changes and their evolution, and their effects on observations of cosmic Xray sources are described here in detail. Furthermore, our methods and solutions to counter these effects through analysis and software are also presented.

Key words: X-rays; detectors; CCDs.

1. INTRODUCTION – THE PROBLEM

The EPIC focal plane spectrometers on *XMM-Newton* use CCDs to record the images and spectra of celestial X-ray sources focused by the three X-ray mirrors. There is one camera at the focus of each mirror, and two of the cameras (hereafter, MOS1 & MOS2) contain seven MOS CCDs, each combining high-quality imaging with near-Fano-limit spectral resolution (Turner et al. 2001).

Throughout the lifetime of the *XMM-Newton* mission, a thorough and detailed programme of instrumental calibration has been ongoing. Over the years, within the analysis of celestial X-ray source spectra, a curious phenomenon at the very lowest energies has been observed in the MOS detectors, and this effect can be seen by referring to Fig.1. Here, two MOS2 spectra are shown of the isolated neutron star RX J0720.4-3125 from both early in the mission (revolution 175) and from later in the mission (revolution 622). In both cases, the open (\approx no attenuation) filter was used. This source was believed to be a constant flux point source ¹, and thus the



Figure 1. MOS2 spectra of the isolated neutron star RX J0720.4-3125 from revolution 175 (black) and from revolution 622 (grey). A shift in spectrum to lower energies is clearly seen.

observed change in the spectrum was deemed due to instrumental effects. A similar, though not identical change is also seen in the MOS1 spectra. Once we were able to exclude many instrumental effects, including PSF, filter transmission and quantum efficiency changes, then it became clear that there was some intrinsic change in the redistribution properties of the CCDs of both MOS cameras, manifesting itself as a shift in the spectrum to lower energies, the effect being most pronounced at lower energies (below ~ 0.5 keV). This effect was seen in many bright soft sources (e.g. Zeta Puppis, Revs 156 & 542), though curiously, as we shall see, not in all observations.

2. OBSERVATIONS OF 1ES0102-72 AND 'THE PATCH'

The various observations of the supernova remnant 1ES0102-72 proved invaluable in helping to solve the puzzle. We can be extremely confident that this remnant, being an evolved and resolved (angular diameter \sim 1 arcminute) source, is a constant source in terms of flux and spectrum. Prior to revolution 850, 10 MOS1 and

¹As it turns out, this source is now not believed to be a truly constant source; small flux variations (far smaller than would account for the observed changes) are believed to have been seen.



Figure 2. 10 MOS1 spectra of the SNR 1ES0102-72 from Revs. 65–803. One observation (from Rev. 447) clearly stands out as showing a shift in spectrum to lower energies.

11 MOS2 observations had be made of 1ES0102-72, all in the same mode ('Large Window') and with the same filter (thin). (The 'missing' MOS1 observation was performed in timing mode). In analysing all the spectra in a thorough and self-consistent way, we saw that all the low-energy spectra appeared the same, as expected, except for one MOS1 observation (Rev. 447), and for two MOS2 observations (Revs. 433 & 447), where the same shift in spectrum to lower energies was observed (The MOS1 case is shown in Fig.2). (Note that the MOS1 observation from Rev. 433 is the 'missing' timing mode observation.). One can see from Fig.2 that the spectrum shift here manifests itself as an increase in flux below 0.35 keV, together with a slight decrease in flux in the 0.35-0.55 keV range - i.e. an energy redistribution effect.

In forming images of the remnant in this very lowest energy band (0.1-0.35 keV), we were able to see (Fig.3) that both the MOS1 and MOS2 images from the 'good' observations looked markedly different from the corresponding images from the 'bad' observations – the 'bad' observations show a low-energy enhancement, or *patch* covering approximately one-half of the remnant.

It was therefore implicit in this that the enhancements seen in the Rev. 447 spectra were related to the 'patches' seen in the images, and to test this, spectra were extracted from the 'on-patch' and 'off-patch' regions of the remnant in the Rev. 447 observation, and from the corresponding remnant regions in the other observations, as delineated by the lines in Fig.3. Spectra from a 'good' observation, and from Rev. 447 are shown in Fig.4. It can be clearly seen that the spectral enhancement at low energies and the small deficit at slightly higher energies are due to the 'patch' visible in the images.



Figure 3. Low-energy (0.1-0.35 keV) smoothed MOS1 and MOS2 images of 1ES0102-72 from a 'good' observation (Rev. 247) and a 'bad' observation (Rev. 447). The 'bad' observations show a low-energy 'patch' over one-half of the remnant.



Figure 4. MOS1 and MOS2 spectra extracted from the two halves (black: 'patch', grey: 'non-patch') of 1ES0102: (top) for a 'good' observation – Rev. 375, and (bottom) for a 'bad' observation – Rev. 447. The spectral enhancement is clearly due to the 'patch' region.



Figure 5. Co-added all-pattern, all-energy central CCD images from all imaging mode MOS observations (up to Rev.~900) (central regions shown). Grey-scale and contours show numbers of photons incident. The RGS-and pn-prime boresights (for MOS1 and MOS2) are also marked.

2.1. The 'Patch' – Where is it?

So, what is this patch, and why is it only seen in a few observations? The answer to this second question became clearer when we looked at the observations in more detail. Almost all of the MOS observations were set, usually due to requirements of the pn camera, such that the remnant was not placed directly at the centre of the MOS detectors, but was usually offset (by $\sim 2-3$ arcminutes). In fact the *only* observations where the remnant was placed at the centres of the MOS detectors were the observations in Rev. 433 & 447 – i.e. the *only* observations where the MOS 'patches' and the corresponding spectral shifts were observed.

This suggested that the 'patches' have something to do with the large numbers of photons incident at the very centres of the MOS detectors. Most XMM-Newton observations are performed in such a way that the target source lies at the optimum position in one or more of the main instruments. The spacecraft has been constructed such that these optimum positions, the individual instrument boresights, lie approximately coaligned. As most observations have been set up with either pn or RGS as the 'prime' instrument, these two boresights, the pn boresight and the RGS boresight (which lie very close to one another, separated by only ≈ 10 arcseconds) are the aimpoints of the vast majority of all the XMM-Newton observations. Consequently, these areas will have been impacted by very many photons. To test this, and obtain the degree of photon incidence, we co-added all-pattern, allenergy central CCD images from every single imaging mode MOS observation (up to Rev. ~ 900). The central regions of the central MOS CCDs are shown in Fig.5, and show that the peak in photon incidence does indeed lie at the centres of the MOS detectors, in a roughly oval region surrounding the positions of the RGS- and pn-prime boresights.



Figure 6. The 10 MOS1 spectra of 1ES0102-72 from Fig.2 plus those from Revs. 894/900. These more recent spectra show an even more marked behaviour in terms of a shift in spectrum, compared with the only previous on-boresight observation (Rev. 447).

2.2. The 'Patch' – How big is it?

In an effort to test our hypotheses so far, and to ascertain the size of the 'patches', an on-boresight raster observation of 1ES0102-72 was performed in Revs. 894/900 (of the 4 observations, one was very effected by flare activity). In looking first at the spectral properties, it was seen that all the Revs. 894/900 spectra showed similar spectral-shift behaviour to that seen in the earlier onboresight (Revs. 433/447) observations, but to an even greater degree (the MOS1 spectra are shown in Fig.6). The situation is similar in the case of MOS2, but with subtle differences: In performing the 'on-patch'-'offpatch' spectral analysis, as for Fig.4, we see that, in the case of MOS1, the on-patch effect may have already reached a peak by Rev 447, with little evolution thereafter, whereas off-patch, a moderate evolution in spectral shift is still seen at later times. In the case of MOS2, the situation appears the same, although a lag is observed with respect to MOS1 - the MOS2 on-patch effect has not yet reached a peak by Rev 447, and there is moderate evolution thereafter (perhaps reaching a peak), and offpatch, only a little effect is seen by Rev 447, and moderate evolution is seen thereafter.

Keeping in mind the idea that the patch is an area on the detector, not on the remnant, it was possible to create an image of the patch, using (for each MOS) the following method: All 'good' off-boresight sky (i.e. RA/Dec) images were mosaiced together to obtain a 0.1-0.35 keV image of the non-patch remnant. Using our knowledge of the remnant position on the detector and the observation position angle, this mosaiced image was rotated and flipped to the correct detector position and orientation for each 'bad' on-boresight pointing. Correcting for the relative exposures, this rotated/flipped image was subtracted from each 'bad' on-boresight detector-coordinate image, to obtain images of the remainder – the patch. A final

4



Figure 7. Final 'torchlight-corrected' images of the MOS2 patch (see text): left, raw; right, smoothed. (The crosses mark the pn- and RGS-prime boresights.)

correction is necessary to account for the unusual effect of the patch only being visible when the SNR illuminates the particular area of the detector – in effect, 1ES0102-72 acts rather like a torchlight. Once this correction is made, raw and smoothed final mosaics of the MOS1 and MOS2 patches can be constructed (the MOS2 patch is shown in Fig.7).

3. COUNTERING THE EFFECTS OF THE 'PATCH'

3.1. Software

The low energy redistribution function (RMF) of the MOS CCDs has a complex shape, in that the main photopeak has a secondary component (a shoulder) which relatively increases with decreasing energy, until, at the very lowest energies, it is the dominant component (see Fig.8). A new on-boresight rmf was constructed to account for the temporal changes seen in 1ES0102-72, RX J0720.4-3125, Zeta Puppis and other sources. The form of this was such that the original (Fig.8) shoulder had now evolved into a flatter 'shelf', of lower amplitude, but extending to lower energies.

This has also now been incorporated into the *XMM*-*Newton* Science Analysis Software (the SAS), such that, as of SAS v6.5, there are now *three* RMF regions on each of the two MOS detectors – a 'patch core' region, a 'patch wings' region and an 'outside patch' region (see Fig.9). This, in combination with the 10 temporal epochs now considered in the SAS, gives rise to a total of 60 MOS RMFs in the current calibration files. For a source extracted close to the patch (e.g., as in Fig.9), a PSF- or flat-weighted average RMF can be constructed (automatically in the SAS) from the three region-defined RMFs (making use, of course, of the calibration files from the correct epoch).

Has this then improved the situation? Various tests have been performed on a large number of sources, and a great improvement has been seen overall. Fig.10 shows an on-boresight patch-effected spectrum from the core



Figure 8. The low energy redistribution function (RMF) of the MOS CCDs (ground calibration measurements: Orsay synchrotron). The secondary component (shoulder) relatively increases with decreasing energy, until it is the dominant component.



Figure 9. The XMM-Newton Science Analysis Software (SAS) situation, as of SAS v6.5: Three RMF regions are considered on each of the MOS detectors (see text).



Figure 10. Improvement in RMFs: Usage of a SAS 6.5 RMF (grey) shows a great improvement over usage of a SAS 6.1 RMF (black) in fitting an RGS fluxed model to an on-boresight patch-effected spectrum of the core of Zeta Puppis from Rev. 795.

(0-15 arcseconds) of Zeta Puppis from Rev. 795. RMFs have been constructed using SAS 6.1 and SAS 6.5, and a high-resolution RGS fluxed model has been used to fit the data. As can be seen, usage of the SAS 6.1 RMF gives rise to a very poor fit, particularly at low energies. Usage of the SAS 6.5 RMF however, gives rise to a very much improved fit. Note also that tests performed on the wings (15-40 arcseconds) of Zeta Puppis show an improvement as well with SAS 6.5, but it is not so marked, as the effect of the patch is not so strong in the wings, at least at the present time, as discussed earlier.

3.2. Hardware

As regards the patches, and what is happening physically within the CCDs, the situation is not entirely clear. A single MOS pixel has an etched area (created to improve the low-energy quantum efficiency), situated near the centre of the surface area of the pixel. Typically, single pixel events (mono-pixels) are detected away from pixel edges, and therefore the majority of these are detected from these etched (open phase) areas. Conversely, double pixel events (bi-pixels) are detected from the pixel edges, i.e. away from the etched areas, and tend to be underneath the electrode structure. It has long be known, e.g. from calibration data taken pre-launch, that there is a difference in the redistribution shapes of mono- and bipixels, in that the charge loss shoulder in mono-pixels is much stronger than that in bi-pixels. The probable cause of this is thought to be that the charge collection in the open (etched) phase is less efficient, due to the structure of the potential field near the surface. Whatever the cause is, we are now observing that this potential structure is changing with time. This, together with the fact that we have a spatial coincidence of the area where this change is occurring most markedly and rapidly with the area of

To this end, we are planning to reproduce the 'patch effect' in the X-ray test facility at Leicester University, using undamaged and proton-damaged CCDs of the same batch as those flying on *XMM-Newton*. MCP optics have recently been added at the optical centre of the Leicester facility to focus a beam of bremsstrahlung X-rays from the low-energy source of around 1.5 keV. We will then be able to monitor the response of these CCDs at low energies.

4. CONCLUDING REMARKS

This paper can be summarized as follows:

- A change in the redistribution properties of the *XMM-Newton* EPIC-MOS central CCDs has been discovered.
- The effect is such, that photons up to ~ 0.5 keV are redistributed to lower energies.
- The effect is seen to be evolving with time.
- The effect is seen to be spatially localized, and is greatest at the boresights of the instruments, where most of the incident X-rays over the mission lifetime have impacted.
- Detailed observations of the SNR 1ES0102-72 have now yielded the position and size of the effected 'patch'.
- Temporal- and spatial-dependent response matrix generation has now been correctly implemented in SAS 6.5 to account for the effects of the 'patch'.
- We are planning to reproduce and test the 'patch effect' in the X-ray test facility at Leicester.

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EPIC CALIBRATION (ANECDOTES)

FROM 3 YEARS BEFORE TILL 6 YEARS AFTER LAUNCH

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ABSTRACT

XMM-Newton has been extensively calibrated on ground and in orbit. The main calibration phase lasted from 3 years before launch up to now and is still ongoing. We will review the general approach of calibrating a CCD technology based X-ray camera taking into account all major calibration steps and improvements until now. This includes an overview of the calibration strategy for various physical phenomena regarding X-ray CCDs and the way we chose to organize those in calibration software and data files.

Furthermore we like to present some lessons learned throughout the whole calibration process that may be of use for future experiments to be calibrated. Note that the 'anecdotes' have only been given during the talk and are considered 'impossible' to be transformed into the paper.

1. THE XMM-NEWTON EPIC CAMERAS

XMM-Newton (Jansen et al. 2001) was launched in December 1999 on an Ariane 504 rocket from French Guyana. Its six instruments are operated in parallel through the course of a 48-hour highly elliptical orbit. Three Wolter type-1 telescopes with 58 nested mirror shells focus X-ray photons onto the five X-ray instruments comprising the European Photon Imaging Camera (EPIC) (Strüder et al. 2001, Turner et al. 2001) and the Reflecting Grating Spectrometers (RGS) (den Herder et al. 2001). The Optical Monitor (OM) (Mason et al. 2001), employing a 30 cm Ritchey Chrétien optical telescope, can perform parallel optical observations of the same field.

EPIC is comprised of three cameras employing two distinct detector technologies. The two EPIC-MOS cameras use front illuminated EPIC-MOS (Metal-Oxide Semi-conductor) CCDs as X-ray detectors, while the EPIC-pn camera is equipped with an EPICpn (p-n-junction) CCD. Both have been specially developed for XMM-Newton. EPIC provides spatially resolved spectroscopy over a field-of-view of 30' with moderate energy resolution. The EPIC cameras can be operated in various observational modes related to the specific readout strategies in each mode. For a detailed description of the modes see Kendziorra et al. (1997), Kendziorra et al. (1999), Kuster et al. (1999) and Ehle et al. (2003). The RGS is designed for high-resolution spectroscopy of bright sources in the energy range



Figure 1: The EPIC-pn (upper) and EPIC MOS (lower) focal planes

from 0.3 to 2.1 keV. The OM extends the spectral coverage of XMM-Newton into the UV and optical, and thus opens the possibility to test physical models of source spectra against data over a broad energy. The six OM filters allow colour discrimination, and there are two grisms, one operating in the UV and one in the optical, to provide low-resolution spectroscopy.

2. GENERAL APPROACH OF CALIBRATING A CCD TECHNOLOGY BASED X-RAY CAMERA (EPIC)

The first plans for EPIC calibration have been started in June 1995 with the system calibration document by the 'XMM system calibration team' that outlined the principle calibration topics and first ideas how to proceed with the calibration. Then various phases of calibration have been carried out starting always from first measurements at the individual small test facilities at the PI institutes leading then to major calibration campaigns at the facilities mentioned later. It is difficult to give a sharp step where development ends and where calibration starts. However we consider the mainstream of calibration only as the calibration campaigns with the fully integrated instruments.





Figure 2: The two most important ground calibration facilities for XMM-Newton: Upper: the PANTER test facility at Neuried/Munich. Lower: The Orsay LURE synchrotron

In principle calibration is divided up in ground and in orbit calibration where on ground the main calibration of all system components is done with a still virginal system. No time dependence measurements are possible per definition since the instruments are not exposed to environments that change their behaviour.

After launch the ground calibration needs to be verified and possibly refined for the first orbit changes or unexpected behaviour. As of launch the system is now exposed to orbital environment (radiation, temperatures, low pressure...) and needs to be monitored carefully in order to track time variability.

2.1 Ground calibration

The major part of the EPIC ground calibration has been carried out at the PANTER test facility at Munich and the LURE synchrotron at Orsay near Paris. For EPIC-pn ~ 4300 man-hours in calibration plus 4 persons maintaining the test facility and 5 people that integrated the instruments at the test facilities various times have been spent. For the EPIC-MOS the number for the actual calibration was higher by a factor of two since more cameras had to be calibrated.

3. CALIBRATION STRATEGY FOR VARIOUS PHYSICAL PHENOMENA REGARDING X-RAY CCDS

We highlight in the following some of the XMM-Newton EPIC calibration topics and their treatment. Details can be found in the regular updated 'EPIC Status of Calibration' document at the XMM-SOC calibration pages and in the CCF release notes.

3.1 Imaging

The PSF is the spatial distribution of light in the focal plane in response to an observed (monochromatic) point source. The PSF integrates to 1 over the infinite focal plane.

Measurements at PANTER for various monochromatic lines in combination with simulations using SCISIM and various in orbit source measurements have been used to derive an analytical model of the PSF with a King function.

After launch problems with ground calibration concerning spectral shape and normalization of spectra for different extraction regions have been encountered and a refinement of the parameters of the PSF using the Active Galaxy MCG-06-30-15 was performed.

3.2 Effective area

The effective area is the collecting area of the optical elements and detector system of the EPIC cameras as a



Figure 3: EPIC-MOS effective area for various filters

function of energy. It is a combination of the collecting area of mirror, the transmission of the gratings (for the MOS), the filter transmission, the Quantum Efficiency of CCDs, and the Vignetting of the whole system.



Figure 4: Vignetting campaign with various observation of the SNR 3C58 to determine the exact position of the optical axis of the telescopes

Mirror effective area measurements have been performed at PANTER for all mirror modules. The thick filter throughput was measured at Bessy and the thin and medium filters have been calibrated at the Osservatorio Astronomico di Palermo. Long measurements for QE for various monochromatic lines have been carried out at PANTER and in addition edge scans for Si and Au have been performed at the LURE synchrotron at Orsay.

After launch the EPIC-pn-QE needed some refinement due to a different thickness of wafer and SiO_2 layer than originally assumed.

The mirror parameters have also been refined around edges using very bright sources that gave a much higher statistical accuracy in comparison to that we could reach with our ground measurements.

The vignetting needed a recalibration since the optical axis turned out to be at a not exactly determined position. For that campaign we used various pointings of the SNR 3C58.

3.3 Energy redistribution

The energy redistribution is the energy profile recorded by the detector system in response to a monochromatic input. It is mode and time dependent and difficult to treat especially at low energy where one is facing a large interplay between redistribution and effective area.

Very long measurements had to be performed at PANTER for various monochromatic lines and also edge scans at LURE for Si and Au could be used to exactly model the spectral response behaviour.

It should be mentioned here that due to a failure of the EPIC-pn flight model during a thermal vacuum test the EPIC-pn flight spare unit had to be used finally on XMM-Newton. This unit had not undergone an as deep calibration assessment like the flight model especially on redistribution matters, since those measurements are



Figure 5: EPIC-pn response to monochromatic Cu-L ground calibration source

very time consuming and could not be repeated for the flight spare model completely due to time constraints facing the launch of XMM-Newton. For that reason we expected to refine especially for the EPIC-pn the redistribution parameters in orbit. This was done using various Blazars and the isolated neutron star RXJ1856-3754.



Figure 6: Spectral fit of the EPIC-MOS1 camera before (black) and after (red) correct treatment of the time and spatial dependent response matrices

The MOS cameras needed a special treatment with a combination of time and spatial dependent redistribution due to evolving patch at the boresight position of the focal CCDs (Read 2005).

3.4 Gain/CTI

CTI (Charge Transfer Inefficiency) is the imperfect transfer of charge as it is transported through the CCD to the output amplifiers during read-out. The Charge Transfer Efficiency (CTE) is defined as 1-CTI. Gain is the conversion (amplification) of the charge signal deposited by a detected photon, from ADU (Analogue to digital unit) charge into energy (electron-volts).



Figure 7: In orbit energy calibration with the line rich SNR Cas-A for EPIC-pn

The same measurements as for effective area and redistribution properties for various monochromatic lines could be used to determine the Gain and CTI properties of the EPIC cameras. In addition we used some measurements with a fluorescence tube at LURE for the energy calibration of the fast EPIC-pn modes.

For the same reason as in 3.3 this calibration needed to be refined in orbit, and the original values had to be refined for the flight spare model using line rich SNRs N132D and Cas-A. The time dependent CTE degradation in orbit due to particle radiation is monitored with the internal calibration sources (Al-K and Mn-K lines) and updated accordingly (Harbarth 2005).

3.5 Timing

Chopper measurements down to 1 ms Period carried out by the University of Tübingen and the PANTER facility have been the basis for the EPIC-pn timing calibration.

After some debugging of the *barycen* code after launch the EPIC-pn Timing accuracy is monitored regularly using the Crab and other pulsars and comparing the XMM-periods with radio data (Caballero 2005).

3.6 Background

Long CLOSED measurements at PANTER and CLOSED measurements in orbit in combination with various BG models for particle radiation, internal and astrophysical background provide the basis for the treatment of the EPIC background. Currently EPIC is putting strong effort to provide the community with improved tools to treat the EPIC background in the appropriate way.

4. ORGANIZATION OF CALIBRATION SOFTWARE AND FILES

The XMM-Newton calibration is organized by the Science Analysis System (SAS) and the so called Current Calibration Files (CCF). Processing XMM-Newton data, the user will need both the SAS and the CCFs in order to create event files that are up to date regarding the newest calibration knowledge. Operated on an individual observation the SAS will check locally the available calibration information and pick out the most up-to-date calibration combination applicable for the data to be processed.

Saying that it is absolutely recommended to the user to check for SAS and CCF updates as often as possible, best with an automated procedure (as it is explained at the XMM-SOC web-pages). The philosophy of SAS and CCF is the following: the SAS contains all calibration-code necessary to correct the data and the CCF files contain the parameters needed by the calibration code.

Usually a SAS update is provided every year, while CCF updates can be expected every day, when new calibration knowledge is available to the instrument teams. This provides a very flexible system that allows the calibration team to transfer the latest calibration knowledge very fast to the community. Every new or updated CCF is explained by a Release Note that is available from the XMM-SOC web site and allows the user to judge if the calibration update is relevant for her/his data analysis and if so reprocessing of data is required.

5. MAJOR CALIBRATION STEPS AND IMPROVEMENTS

The following list gives a chronological list of major improvements of the calibration. Details on all topics can be found in the calibration Release Notes at the XMM-Newton SOC pages or in the various publications on XMM-Newton calibration.

- 1997-2000: Ground calibration PANTER, Orsay, Bessy, University of Tübingen
- 1998 February- October: Main phase of ground calibration
- Launch 10.12.1999
- 19.01. 16:19 h first light EPIC-pn
- 21.01. 15:11 h first light EPIC-MOS
- 2000 Feb-June: CAL-PV-phase
 - o 22 calibration targets
 - o 29 performance verification targets

- CTE in-orbit calibration refinement and RMF tuning
- EPIC-pn offset calculation method changed
- 2001: EPIC-pn fast modes energy calibration refinement
- 2002:
 - o relative timing problem solved
 - EPIC-MOS CTE degradation requires epoch dependent energy calibration
 - further down-cooling of the MOS cameras to slow down degradation process
- 2003:
 - vignetting recalibration (optical axis)
 - major cross calibration campaign started
 - EPIC-pn QE refinement
- 2004:
 - o recalibration of PSF
 - recalibration of astrometry
- 2005:
 - discovery of spatial and time-dependent redistribution change in both MOSs \rightarrow epoch and spatially dependent RMFs
 - recalibration of EPIC-pn effective area and RMF
 - micro-meteoroids (see A. Abbey these proceedings)

6. LESSONS LEARNED

Calibration seems to be a never ending story about learning lessons. Trying to motivate future calibrators to perform good calibration we like to stress here some points of the calibration where future missions may learn from the experience of XMM-Newton.

We consider the ground calibration as very intense and important task for the whole calibration process and recommend to carefully plan, execute and document that process. Given the fact that ground calibration information may be still useful and needed more than 10 years after the actual measurement it is crucial to transfer that knowledge from one calibration generation to the next for missions with such a long planning and life time like XMM-Newton.

Also we see the cross calibration of different cameras and camera models as a very important issue where future missions may already improve before launch. We know that this statement is perhaps too optimistic given the time and man power constraints in such calibration campaigns, but where possible cross calibration measurements are recommended as early as possible.

The in orbit calibration and monitoring of the evolution of the cameras is a very important the quality of the calibration driving factor. We recommend to carefully prepare an in orbit calibration plan that should be discussed very much in advance of the launch of the instruments. Understanding that fighting for calibration time in competition with the scientific observations which are of course the more important once is a tough job, we recommend keeping the pressure for the need of regular and non regular calibration observations. Only a good set of calibration observations can guarantee a successful scientific performance of the observatory.

In addition we see the strong need for a set of standard calibration sources for the X-ray regime. Given the luxury of having 6 satellites (XMM-Newton, Chandra, RXTE, Swift, Integral, Suzaku), that have X-ray instruments as their payload, in orbit simultaneously and for the coming years, we strongly recommend to form an international calibration group that may steer the cross-calibration efforts in this field.

7. AKNOWLEDGEMENT

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9. ANNEXUS: CALIBRATOR SNAPSHOTS



STATUS OF THE XMM-NEWTON CROSS-CALIBRATION WITH SASV6.5.0

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ABSTRACT

Further achievements of the XMM-Newton crosscalibration - XMM internal as well as with other X-ray missions — are presented. We explain the major changes in the new version SASv6.5 of the XMM-Newton science analysis system. The current status of the crosscalibration of the three EPIC cameras is shown. Using a large sample of blazars, the pn energy redistribution at low energy could be further calibrated, correcting the overestimation of fluxes in the lowest energy regime. In the central CCDs of the MOSs, patches were identified at the bore-sight positions, leading to an underestimation of the low energy fluxes. The further improvement in the understanding of the cameras resulted in a good agreement of the EPIC instruments down to lowest energies. The latest release of the SAS software package already includes corrections for both effects as shown in several examples of different types of sources. Finally the XMM internal cross-calibration is completed by the presentation of the current cross-calibration status between EPIC and RGS instruments. Major efforts have been made in cross-calibrations with other X-ray missions, most importantly with Chandra, of course, but also with currently observing satellites like Swift.

Key words: XMM-Newton, SASv6.5, calibration.

1. MAJOR CHANGES FROM SASV6.1 TO SASV6.5

1.1. MOS responses now time and spatial dependent

The major change from SASv6.1 to SASv6.5 is the new response generation in *rmfgen* for the EPIC MOS instruments. Using SASv6.1 it has been found that, starting at about rev. 380 and increasing mission duration,

pn and MOS measurements diverge at low energies for most observations. Using supernova remnants, a spatial dependency of this low energy discrepancy was discovered. Further investigations reveal a change in the MOS distribution behaviour at and close to the nominal boresight positions (Fig. 1), whereas the redistribution outside these regions does not show any change. These spatial dependency indicate that X-ray and/or focused particle radiation changed the physical performance of the CCDs.



Figure 1. Visualisations of the MOS patch: the chip region around the bore-sight positions shows time dependent redistribution behaviour. The new MOS response generation takes into account the time and spatial dependency of these central chip regions.

The new MOS response generation takes into account three time dependent regions and calculates the response according to the selected source region. Using SASv6.5 the previously found low energy discrepancy, evolving with time, is corrected. Examples are provided in sect. 3. A more detailed description is provided in the conference contribution of Andy Read et al.: 'Patching' EPIC-MOS: Temporal and Spatial Dependency of the Detector Response.

Together with the SASv6.5 and its new MOS response generation, a new set of 18 CCF-files has been published, for nine time epochs now modelling the spatial dependency by three regions for the central CCDs. Warning: Using SASv6.1 together with the new set of CCF-files, *rmfgen* could create responses with strange features.

1.2. Improvement of arfgen

Since revolution 961 a new hot column has appeared on MOS1 CCD1 due to an impact of a micrometeorite dust particle on MOS1 CCD1. This new defect is leaking into the whole column. As a consequence, the offset of this column is raised by about 20 ADUs, therefore generating a lot of noise events at low energy above the low energy threshold, and the whole column is identified as bad by embadpixfind and masked out in the calibrated event list. As this column passes a few pixels from the nominal target position on CCD1, a significant fraction of the on-axis source PSF is affected. If the selection #XMMEA_EM to the MOS event list is applied to generate spectra of on-axis sources, only the bad column is marked bad but not the adjacent columns. This missing column is taken into account by arfgen in the computation of the effective area.



Figure 2. MOS1 exposure affected by the new hot column after the possible micrometeorite impact of rev. 961. Using FLAG==0, also the two adjacent columns are masked. The new arfgen version of SASv6.5 now takes into account these adjacent missing columns in the computation of the effective area.

If the more conservative selection flag FLAG==0 is used for the analysis, also the two adjacent columns are masked, therefore 3 columns are removed, causing the loss of up to 10-15% of the flux of an on-axis source. The SASv6.1 did not take into account these adjacent missing columns in the computation of the effective area. Therefore the absolute flux/normalisation of a source was too low. The new *arfgen* version of SASv6.5 now takes into account these adjacent missing columns.

1.3. Improvement of embadpixfind

In SASv6.1, the two MOS pipeline tasks *emproc* and *emchain* used different routines to search for bad pixels. The first used the general task *badpixfind*, whereas the latter used the more advanced, to the MOS data reduction adapted task *embadpixfind*. Thus, the resulting MOS eventlists of both pipelines could differ distinctly. In SASv6.5, both pipeline tasks are using the *embadpixfind* routine to detect bad pixels and the resulting event lists of both pipeline tasks are completely equivalent now.



Figure 3. Example for the new rejection algorithm used by embadpixfind. Top: previous algorithm used in SASv6.1 could erroneously mark columns as bad. Bottom: SASv6.5 image of the same MOS2 exposure.

Due to offset variations from column to column, the previous version of *embadpixfind*, in rare cases, could remove single columns by flagging them bad erroneously (Fig. 3, top). In specific observations, the central pixel of the PSF could be marked as a bad pixel and removed from the event list. A new rejection algorithm prevents erroneous identifications of bad columns and pixels (Fig. 3, bottom).

2. EFFECT OF NEW PN REDISTRIBUTION: LOW ENERGY IMPROVEMENT

X-ray spectra of blazars are expected to show a featureless continuum. Spectral fits of a set of blazars show common systematic s-shape pn residuals at the low energy end of the pn best fits (Fig. 4). Using this set of blazars, the pn redistribution has been optimised and already published via a CCF-file in 2005 May.



Figure 4. pn best fits for a set of blazars. Top: Common s-shape residuals using old pn redistribution CCFs. Bottom: Flat residuals using new pn redistribution CCFs (published 2005 May).

3. EXAMPLES FOR DIFFERENT EPOCHS

The effect of the new MOS response generation with its time and now spatial dependency is presented using two sources, the quasar 3C 273 as a continuum source example, and 1ES0102-7219 as a coronal source example.

All 3C 273 observations presented in Fig. 6 were performed in the EPIC small window modes and the medium filters. As fit model, a double power law model with galactic absorption is used. The 3C 273 series show a good agreement of all EPIC instruments at all epochs. The time dependent low energy discrepancy, increasing with time, is solved by the new MOS responses. At low energies below 0.8 keV, the RGS and EPIC still disagree. The spectral summary of the 3C 273 series is:

- pn bump up to 10% between 0.4-0.5 keV
- MOS2 bump up to 20% at 0.2-0.4 keV
- Above about 5 keV, pn is lower than MOS by 10%
- RGS decrease by 10-20% at lowest energies during the mission.

The low energy (0.4-0.8 keV) flux stability using 3C 273 is presented in Fig. 5 with pn flux refered to one. The MOS to pn ratios decrease by less than 5% over the mission, the RGS ratios decrease by 10-20%.



Figure 5. Low energy (0.4-0.8 keV) flux stability using a series of 3C 273 observations. There are only small changes in the MOS to pn ratios, but still larger changes in the RGS/pn ratios.

All observations of 1ES0102-7219 presented in Fig. 7 were performed in small window mode for pn and the large window modes for MOS. In rev. 375, 521 and 981 the thin filters were used, in rev. 888 the thick filter was used for all EPICs. For pn small window mode, the background correction is difficult due to the small size of the CCD window, whereas for the MOS the background could be taken from the outer CCDs. The fit model includes 40 lines plus absorbed bremsstrahlung. The line energies were fixed to laboratory values and the widths are determined by RGS.

The 1ES0102-7219 series show that the pn response underestimates redistribution, most evident the O-lines. Above about 0.6 keV, the agreement between RGS and EPICs is good. For later epochs, the decrease of the RGS low energy flux become evident again, hence the combined fits are unreliable at low energies. In rev. 888, the thick filter measurement, large pn-MOS discrepancies are present below 0.5 keV.



Figure 6. Continuum source 3C 273 for the different time epochs rev. 277, 563, 655, 835 and 1023 (top to bottom). All observations were performed in EPIC small window modes and the medium filters.



Figure 7. Line source 1ES0102-7219 for the different time epochs rev. 375, 521, 888 and 981 (top to bottom). All observations were performed in small window mode for pn and the large wondow modes for MOS. In rev. 888 the thick filters were used, all others were using the thin filters.

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The problem is thought to be not related to the filter model but to the redistrubution at small count statistics.

4. EXAMPLES OF OTHER SOURCES

In this section we present examples of different sources at different epochs. PKS0558-504 (Fig. 8) was observed in rev. 153, an epoch before the MOS patch was present. The pn was in small window mode, MOS in large window mode. All EPICs used the thin filter. This observation is an example of a perfect agreement between all EPIC instruments.



Figure 8. PKS0558-504 in rev. 153, before the MOS patch was present. Perfect agreement between all EPIC instruments.

At the PKS2155-304 observation in rev. 545 (Fig. 9) and for H1426+428 in rev. 1012 (Fig. 10), the MOS patch was present. Both observations used the EPIC small window modes with the medium filter. The spectra show a good general agreement for the total energy range. The largest discrepancies are present between 0.4-0.8 keV, where the MOS are lower than pn by 10-15%. Above 5 kev, the pn is lower than the MOS by up to 10%.



Figure 9. PKS2155-304 in rev. 545. with MOS patch present. Largest discrepancies present between 0.4-0.8 keV.



Figure 10. H1426+428 in rev. 1012. Discrepancies are reduced to max. 10%.

The isolated neutron star RXJ1856-3754 has been observed in rev. 427, 878 and 968 using pn small window mode and the thin filter. The flux variations were less than 1%, proving the low energy stability of the EPIC pn. With SASv6.1, the absorption column was fitted to zero for pn. Using the new CCFs published 2005 May, the $N_{\rm H}$ is not disappearing any more, even if the fitted value is lower than the value obtained from the deep Chandra observation. Fig. 11 presents the rev. 878 observation with all EPICs in small window mode and thin filters. MOS and pn agree within 10% down to lowest energies.



Figure 11. RXJ1856-3754 in rev. 878. MOS-pn agreement within 10% down to lowest energies.

5. XMM-NEWTON VERSUS CHANDRA

The first example presents a simultaneous observation of PKS2155-304 observation in rev. 362 (Fig. 12). The general spectral shape measured by XMM-Newton EPIC and Chandra ACIS/LETG above about 1 keV agrees well, with Chandra normalisations being higher than the EPIC ones. Below 1 keV and compared to EPIC, the ACIS/LETG residuals increase to lower energies whereas the RGS residuals decrease by about the same level.



Figure 12. Simultaneous XMM-Newton and Chandra observation of PKS2155-304 in rev. 362.

An example for a simultaneous observation of XMM-Newton with Chandra ACIS/HEG and ACIS/MEG is presented in Fig. 13. H1426+428 was observed in rev. 1015. Again, the general spectral shape agrees very well between XMM-Newton and Chandra. Especially between 0.8-2.0 keV all instruments agree within 15% in normalisation. Above 2 keV, the ACIS/HEG shows a slightly flatter slope than EPIC. At high energies, MOS are closer to ACIS/MEG than pn.



Figure 13. Simultaneous XMM-Newton and Chandra observation of H1426+428 in rev. 1015.

6. XMM-NEWTON VERSUS SWIFT

A simultaneous observation of XMM-Newton and Swift was performed on H1426+428 in rev. 1012 and the result is presented in Fig. 14. The residuals show a good agreement of all instruments between 0.6-3.0 keV. The Swift XRT measures a steeper slope at high energies than the EPICs. Below 0.6 keV, large discrepancies are present.



Figure 14. Simultaneous XMM-Newton and Swift observation of H1426+428 in rev. 1012. Swift data courtesy of Sergio Campana.

7. CONCLUSIONS

With the new mechanisms for time- and spatial dependent MOS redistributions in SASv6.5, together with the published corresponding new set of EPIC MOS-CCFs, the EPIC low energy issue is about to be solved. The new pn CCFs are already available since 2005 May. RGS show a low energy flux difference of about 10% at launch. The sensitivity at longest wavelengths has decreased by 10-20% over the mission. The status using SASv6.5 is that EPIC and RGS are not yet consistent below 0.7 keV.

The next big step in cross-calibration will be the implementation of the best knowledge of RGS into SAS (see J. W. den Herder et al.: Absolute Effective Area Calibration of the XMM-Newton Reflection Grating Spectrometers, this conference).

MICROMETEOROID DAMAGE TO CCDS IN XMM-NEWTON AND SWIFT AND ITS SIGNIFICANCE FOR FUTURE X-RAY MISSIONS

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ABSTRACT

Key words: X-rays; detectors; micrometeoroids; grazing incidence mirrors.

In 5 years of operation there have been 3 cases of presumed micrometeoroid damage at the focal plane CCDs on XMM-Newton. The latest hit resulted in one peripheral CCD in one of the MOS cameras stopping working and the central CCD developing a hot column which showed an unexpected slow decay over several weeks. The Swift XRT camera has already had a hit after 7 months in low earth orbit resulting in an over-range hot column and inability to operate in all modes. This paper discusses the information we have on these hits, ground tests at dust accelerators, probability of damage in the different orbits, and extrapolation to missions such as XEUS in L2 orbit.

1. OVERVIEW OF THE PROBLEM

This paper while largely an overview of micrometeoroid damage to the detectors on *XMM-Newton* and *Swift* tries to give some figures for the debris population in orbit and explains how this debris can get to the detectors. We also give thoughts on other existing missions with grazing incidence optics, details of further research at Leicester and speculation on future X-ray missions such as *Astrosat* and *XEUS*.

XMM-Newton launched by ESA in November 1999 is in a two day highly elliptical orbit with an apogee of c. 114,000 km and a perigee of c. 7000 km. The *EPIC (European Photon Imaging Cameras)* X-ray cameras use CCDs behind thin light blocking filters to record the images and spectra of celestial X-ray sources focused by the three sets of grazing incidence X-ray mirrors of 7.5m focal length. There is one camera at the focus of each mirror, and two of the cameras (hereafter, MOS1 & MOS2) each contain seven *MOS (Metal Oxide Semiconductor)* CCDs manufactured by E2V, while the third camera contains German *pn CCDs* (Turner et al. 2001). The *XRT* camera on *Swift* contains just one of the MOS CCD22s as used on *XMM-Newton* behind a set of 12 nested grazing incidence X-ray mirrors.

XMM-Newton has had a number of events during its 5+ years in orbit. Both pn and MOS cameras have experienced damage in the form of hot pixels sometimes proceeded by light flashes and there is strong evidence that these are due to micrometeoroids. The latest event in March 2005 resulted in the loss of a whole CCD in MOS1. *Swift* in low earth orbit has already sustained one hit after 6 months of operation. The *pn* team visited a dust accelerator in 2002 and showed that particles of micron size can be deflected by grazing incident optics onto the CCD (Meidinger et al 2002).

2. MICROMETEOROID HITS MECHANISM

In the same way that grazing incidence mirrors reflect Xrays, they can also deflect grazing incidence particles. As long as the high-Z surface is sufficiently smooth compared with the particle size and the particles angle of incidence is low enough the mirrors appear to be able to either deflect the particles or to break them up and create a shower. This was established by the MPE dust accelerator tests in 2002. The flux directly entering the telescope will be constrained within a narrow cone defined by the opening angle of the telescope. Both Swift and XMM telescopes with multiple-shell grazing incidence mirrors have similarly small grazing incidence angles, $<0.7^{\circ}$. The MPE work shows that, at small angles, particles scatter essentially parallel to the mirror surface implying inelastic scattering of the particles when they strike the mirror surface. Transverse momentum is lost to the mirror but longitudinal momentum is conserved in the particle or its fragments. This result holds true out to grazing angles of 4°, and possibly beyond (because the MPE measurements stopped at 4°). Fig. 1 shows an SEM photograph of an impact site of an iron particle of



Figure 1. SEM photograph from pn study of an impact site in silicon of a $0.2 - 2\mu m$ iron particle

size 0.2 - $2\mu m$ with a speed of 5km/s in silicon from the MPE study. The light blocking filters are too thin to offer any protection to the CCDs except when the EPIC filter wheel is in the "closed" position.

For a spacecraft like *Swift*, in LEO, particle fluxes impacting on spacecraft surfaces may originate from interplanetary micrometeoroid particles intercepting the spacecraft orbit or from space debris particles created from anthropogenic activities in nearby orbits. The micrometeoroid component takes the form of an isotropic distribution which has been characterised by Grun et al and is sometimes known as the Interplanetary Meteoroid Flux or IMF. In LEO, there is a significant orbit-dependent space debris component, which sits on top of the micrometeoroid distribution. Knowledge of these two components provides a means of evaluating the probability of space particle impacts on *Swift*.

Figure 2 is a plot from a recent study by J. Carpenter 2005 using the ESA Master 2001 model of the meteoroid and debris environment between LEO and GEO as applied to the orbit of the Swift satellite and shows the flux rate for each face of the spacecraft versus particle size. At no time does the XRT have either ram or Earth pointing vectors. Calculations have therefore been restricted to flat plates with left, right, space and wake pointing directions. The XRT pointing direction varies as at it slews about the sky. In this simple model the XRT is assumed to spend equal time in each of the 4 described pointing directions. Once total impacts for each face shown in figure have been calculated, the average $impacts/m^2/sr/year$ is calculated. This is then multiplied by the XRT open area of 250cm². and an assumed acceptance cone angle of $10^{\circ} (\pm 5^{\circ})$ for particles. The calculated number of impacts in the XRT focal plane in one year, by particles with diameters greater than 1μ m is 1.4. The predicted rates for XMM with its mirrors of 1750cm² might be a factor of up to 10X higher as shown in Fig. 3.



Figure 2. Impact flux contributions from each face for Swift

Impact	Impact Event	Impact Event
Parameter	Rate /year	Rate /year
(µm)	XRT 5°Cone	XMM 5° Cone
	half angle	half angle
1	2.4	20
2	0.7	6.0
5	0.2	1.9
10	0.1	1.0

Figure 3. comparison of Swift and XMM impact rates excluding low earth orbit RAM direction

3. XMM IMPACT HISTORY

Each orbit of *XMM-Newton* takes 2 days. The following lists the impacts seen so far:

- Orbit 107 17 July 2000 MOS2 patch of hot pixels on 3 CCDs - questionable whether was due to large proton flare prior to Filter Wheel closing.
- Orbit 156 15 Oct 2000 PN several hot pixels suddenly appear.
- Orbit 325 17 Sept 2001 MOS1 bright flash seen, many new hot pixels.
- Orbit 490 12 Aug 2002 MOS2 bright flash seen, no new hot pixels
- Orbit 961 9 March 2005 MOS1 bright flash seen, bright column developed on central CCD, total loss of CCD6.

3.1. The effect of the suspected impact on orbit 107

The new hot pixels shown in Figure 4 formed a patch on CCDs 1,2 and 7 on MOS2 at the start of orbit 108 but were not present at the end of 107 when a high radiation level was reported. The filter wheel would have been closed for the perigee pass, so should have protected the CCDs. This mystery was never officially solved. There must have been a hit in the time between the end of the observation and the closing of the filter wheel. The distribution of hot pixels suggested that a cloud of debris from an impact higher in the camera had hit the focal plane.



Figure 4. Hot pixels at start of orbit 108

3.2. Impact on pn camera orbit 156

This is an extract from the 2002 SPIE paper on the PN-CCD impact and dust accelerator verification from Norbert Meidinger et al: "XMM was observing Zeta Puppis and was 115000 km from Earth and pointing 60 from the ram direction. The hot pixels generated had energies orders of magnitude higher than those expected due to heavy ions." Figure 5 shows the 35 hot pixels which appeared after this impact covering 6 of the 12 CCDs. The 12 CCDs cover an area of 6cm X 6cm. The circles indicate where several hot pixels are close together with the number shown alongside.

3.3. Impact on MOS1 on orbit 325

This was the first event where a light flash was seen. The first evidence was that in a routine observation the MOS1 camera suffered a "FIFO FULL" error where its data buffers had received too much data. In figure 6 this 3-d image of a light flash was reconstructed from the partial images generated on-board due to FIFO overflow in the limited memory.



Figure 5. Hot pixels on pn camera during orbit 156



Figure 6. Orbit 325 - reconstructed optical flash in MOS1

3.4. Impact on MOS2 on orbit 490

This was first reported as a "FIFO Full" error in MOS2 during a routine observation which happened during the annual Perseid meteor shower and observations had been planned to go no nearer than 15° to the Perseid radiant. The observation would have been 64° from the radiant at this time, and the event was interesting as no hot pixels were generated and it is surmised that it happened high in the telescope because of the more obtuse angle than some of the other grazing incidence ones.

3.5. Impact on MOS1 on orbit 961

The impact on MOS1 during orbit 961 proved to be the most damaging to date in the life of *XMM-Newton*. At 01:30 hrs UT on 09 March, 2005 during a routine observation, the now familiar "FIFO Full" error occurred and the optical flash image in figure 7 was extracted from the



Figure 7. Orbit 961 - optical flash in MOS1

buffers. After the flash CCD6 output was permanently saturated giving no x-ray events and a new hot column of value around 60DN had appeared on CCD1 - figure 8. Investigations took place to determine the failure mode of CCD6 and the conclusion was that there is a hard short from an electrode to the substrate which is injecting large amounts of charge irrespective of clocking. MOS1 now operates with CCD6 switched off. The hot column on CCD1 appeared to reduce a little over successive orbits (figure 9) and a subsequent adjustment to the bias level for the rogue column has restored normal operation. Since the MOS1 damage was extensive, a series of tests were performed during orbit 1042 on the thin optical filter which had been in front of the camera when the impact took place. The bright globular cluster Omega Centauri was observed, and the filter wheel moved by small increments to see if a pattern of out-of-focus light spots could be seen. The test was believed to be able to detect holes down to 50μ m but none were seen. This work is still ongoing, but it does appear that the filter has not been significantly damaged by the impact. This is because each piece of debris is likely to be in the sub-micron/micron range and does not create an enlarged hole in a thin filter.

4. SWIFT IMPACT

On 27 May 2005 *Swift XRT*, only 6 months into the mission the processing log shows the following:

Mode	Count rate	Time
PC	0.80	2005-147-05:21:48.708787
PC	1799.55	2005-147-05:21:51.216076
WT	1034.19	2005-147-05:22:4.7158214
LRPD	45758.71	2005-147-05:22:5.8755013
PUPD	45975.84	2005-147-05:22:7.2480145

This shows that the camera suddenly saw lots of events and went through its modes to the highest count rate mode PUPD. The XRT viewing direction at the time was

Figure 8. Orbit 961 - hot column in CCD1



Figure 9. Hot column trend in CCD1 after orbit 961

 142° from the RAM direction. Because of its large memory buffers *Swift XRT* was able to store all of the single frame of data which occurred at 05:21:51UT on 27 May 2005. Figure 10 shows the light flash stopping at the edge of the field of view. The dark areas in the centre of the bright areas are caused by the sum of the 3 X 3 event pattern exceeding a 4095 upper limit and therefore being interpreted on board as a cosmic ray and not being telemetered.

Figure 11 shows the resultant damage to the *Swift* CCD. The column down the middle of the image and the short columns were not present before the event. The damage does not obviously coincide with the peaks of the light splashes in the flash image.



Figure 10. Light flash on CCD in Swift XRT



Figure 11. Bright columns resulting from the impact on Swift XRT

4.1. Operational effects of the XRT CCD damage

Although we have been able to exclude the hot column from the data on Swift XRT in photon counting and timing modes, we are currently unable make full use of the fast readout mode known as Photodiode mode. This reads out the whole CCD in diagonal strips by means of a column shift followed by a row shift and there is no positional information to remove defects. The hot column raises the background level to between half and full scale depending on the operating temperature. So far the science loss from this has been negligible, but on occasions, the earliest x-ray data from a GRB could be compromised. The spectrum of figure 12 shows a typical noise peak at over half of the ADC range from data taken at -59°C on 23 Sept 2005 while pointing at Gamma Ray Burst GRB050922B. Changes to the gain used in photodiode mode are a possible fix to restore dynamic range at some loss of energy resolution. Another fix might be to read out the "good" half of the CCD avoiding the hot column



Figure 12. Resulting spectrum in PD mode of bright column on Swift XRT

with a need to offset point the spacecraft.

4.2. Filter damage test

Swift has an advantage over XMM in that a light emitting diode can be switched on inside the camera to check filter integrity. Subtracting an early orbit test of the in-flight LED from a post-impact image showed no visible damage to the light-blocking filter which would have been a large bright out-of-focus area(s). So, as with the previous micrometeoroid events it seems that the size of hole which is generated in the filter is insufficient to cause a noticeable light leak yet sufficient to damage a hard silicon dioxide surface.

4.3. Swift pointing directions

Figure 13 shows the directions referenced to the Ram direction in which *Swift* pointed during the first 2 months of operation. Due to operational constraints *Swift* spends most of its time pointing around 90° to the Ram direction so the major flux of low earth orbit debris should not have been a problem.

5. PAST AND FUTURE MISSIONS WITH GRAZ-ING INCIDENCE OPTICS

This is a brief summary of past missions and what is known about the effect of micrometeoroids on the detectors:

 Chandra 6 years in orbit - in similar deep elliptical orbit to XMM-Newton, but no reports of impact damage. This is likely to be due to the geometry since the mirrors have 5X smaller effective area



Figure 13. Swift pointing direction history

than *XMM-Newton*, so if we believe in statistics we should expect an impact anytime now!

- ASCA was in similar low earth orbit to Swift, but no reports of impact damage. Was this due to use of thin foil mirrors of 137m thickness? Perhaps incoming micrometeoroids are not deflected by such mirrors.
- *Rosat* was in a similar low earth orbit to *Swift* but its detectors were probably insensitive to damage from micron size particles. There are no reports of significant gas loss from the imaging proportional counters through window damage during its 9 year lifetime.

Future missions:

- Astrosat will be in a nearly equatorial low earth orbit and will use ASCA-like thin foil X-ray mirrors. Possibly the risk of particle damage may be correspondingly lower. AT UoL we will perform tests on mirror samples to ascertain whether the thin shells deflect micrometeoroids.
- *XEUS* will be in L2 orbit. It has a large mirror with an effective area of 10 x *XMM-Newton* which will produce a considerable potential for impacts. A narrower acceptance angle gives some reduction. Expect several hits per year unless L2 orbit debris is considerably different from XMM orbit. We would recommend that there is considerable effort spent on redundancy and avoiding knock-on effects of damage in one detector affecting others.

6. CURRENT RESEARCH INTO DUST DAMAGE AT LEICESTER

The University of Leicester along with MPE, Keyser-Threde and RKK Energia has been involved in an experiment on the ISS - 756 days in orbit with microchannel plates bearing a 60nm aluminium film. This was able to detect particles down to 14 nm diameter at 20km/s producing a 400nm hole in the foil. The density of holes showed a flux of over 1/m²/s. It is likely that particles of this size may not damage the surface of a CCD, but one can speculate about the cumulative damage to thin filters. J D Carpenter et al 2005. A different experiment has recently been taking place at the Open University light gas gun facility to investigate larger particles and their effects on detectors but so far we have only shattered silicon wafers. It is our intention also to use the dust accelerator at the same location for tests on *Astrosat* thin mirror samples.

7. CONCLUSIONS

Micrometeoroid particles in low and high earth orbit present a considerable hazard to missions with grazing incident optics and impact sensitive detecor arrays. XMM-Newton has experienced approximately one hit per 14 months over its 6 years in orbit. Swift in low earth orbit may have been unlucky to have been hit in 6 months. Although the density of particles is highest in the Ram direction, no known hits occurred in that direction and it is usually avoided. Since the complete loss of a CCD from the last hit on XMM-Newton, we should consider carefully the redundancy aspects of focal planes for future missions. Would we have built Swift XRT with a single CCD had the XMM rev 961 event already occurred at the design stage? There is probably little else that can be done for missions with grazing incidence optics except to continue observing in the most favourable directions and to design mirror baffles so as to reduce the acceptance angle for particle fluences.

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THE GROUND CALIBRATION OF THE BACK-SIDE ILLUMINATED CCD CAMERA OF X-RAY IMAGING SPECTROMETER (XIS) ONBOARD ASTRO-E2 (SUZAKU)

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ABSTRACT

We report on the results of the ground calibration of the back-side illuminated (BI) Charge-Coupled Device (CCD) onboard Suzaku(Astro-E2). The BI CCD has higher quantum efficiency (QE) below ~4 keV than Front-side illuminated (FI) CCDs. By chemisorption charging process, furthermore, the BI chip achieved very good energy resolution comparable to the FI chip. However, several problems were found by our ground calibration. One of them is charge trailing, and we corrected this phenomenon by a newly developed method, "Charge Trail Correction". Another problem is that the constant split threshold, a key parameter for the Grade method, gives a poor performance for the BI chip. Thus we introduced a new Grade method with a variable split threshold depending on the incident X-ray energy.

Analyzing the ground calibration data with these new methods, we built the response function of BI CCD.

Key words: Suzaku, XIS, X-ray CCD, calibration.

1. INTRODUCTION

Suzaku was launched from Uchinoura Space Center (USC) on 10 July 2005 as the Japanese fifth X-ray astronomical satellite, and successfully put into the orbit. Unfortunately, X-Ray Spectrometer (XRS; Mitsuda et al. (2001)), one of the main instruments of Suzaku, became not operational because of helium loss, but all of the other detectors, Hard X-ray Detector (HXD; Makishima et al. (2001)) and XISs, are still working properly. The HXD consists of phoswitch crystal scintillators (GSO/BGO) and PIN silicon solid-state detectors. It has a large energy range of 10–600 keV band, and the sensitivity is higher than any other hard X-ray detectors especially in the 10–200 keV band. XISs are composed of four sensors, which are placed at the focal plane of four X-Ray Telescopes (XRTs). Three of them are the FI CCDs (XIS0, XIS2,



Figure 1. Schematic view of XIS sensor component.

XIS3), and the other is the BI CCD (XIS1). We will describe the BI CCD in detail in the following section.

Figure 1 shows the schematic view of one XIS sensor. Each sensor has a single CCD chip with an imaging area of 1024×1024 pixels. The pixel size is $24 \ \mu m \times 24 \ \mu m$. The field of view and the time resolution (readout time) are $18' \times 18'$ and 8 sec, respectively. The CCD chip is cooled into -90 °C by Thermo-Electric Cooler (TEC) which is controlled by Thermal Controller Electronics (TCE). The chip has four readout nodes and each node reads the signals from 256 columns of the chip, and then these divided regions of the chip are called as Segment A–D. The analog signals from the sensor are transferred to the Analog Electronics (AE) and converted into the digital signals. Then they are sent to the Digital Electronics (DE) and X-ray events are extracted.

All XISs are developed by the collaboration of Massachusetts Institute of Technology (MIT), Japan Aerospace Exploration Agency (JAXA)/Institute of Space and Astronautical Science (ISAS), Kyoto University, Osaka University, Rikkyo University, Ehime University, Kogakuin University, and RIKEN (The Institute of Physical and Chemical Research).

2. DESCRIPTION OF XIS/BI

In the history of Japanese X-ray astronomy, Suzaku is the first satellite which introduces BI CCD. Since there are no gate structure obstructing incident X-rays on the surface of the BI CCD, it has high quantum efficiency (QE) for soft X-rays. Figure 2 shows the QE of FI and BI CCD, which was modeled on the results of our ground calibration. We can see that the BI CCD has much higher QE below ~3.5 keV than the FI CCD. However, because the depletion layer of BI CCD is thinner than that of FI CCD (~ 75 μ m and ~ 45 μ m for FI and BI, respectively), the QE of BI CCD for hard X-rays is lower than that of FI CCD.



Figure 2. Quantum efficiency of FI CCD (solid line) and BI CCD (dash line).

Generally, the charge collection efficiency of BI CCD is poorer than that of FI CCD. Therefore the energy resolution of BI CCD tends to become worse. For example, the energy resolution of Advanced CCD Imaging Spectrometer (ACIS)/BI loaded into Chandra (Weisskopf et al. (2002)) was about two times worse than that of FI devices, even before the launch. The XIS/BI is improved in this problem. Figure 3 shows the structure of the XIS/BI chip. In the chemisorption charging process, the back surface of the wafer is first oxidized. The resulting oxide layer is then coated with a very thin layer of silver. The silver catalyzes dissociation of molecular oxygen on the surface during processing, leaving fixed, negatively charged oxygen atoms on the surface. Then the electric field between the surface and electrode is strengthened, and the collection efficiency of photo-electrons is improved.



Figure 3. Schematic of the XIS/BI chip treated with the chemisorption charging process.

3. GROUND CALIBRATION

3.1. Overview of the Calibration

The CCD calibration task was shared with MIT, Osaka University, Kyoto University, and JAXA/ISAS. After the simple chip level calibration at MIT, the detailed wide band calibration combined with flight AE was done by Osaka University and Kyoto University. Osaka University group investigated the low energy (< 2 keV) X-ray response of the sensor using grating spectrometers. On the other hand, Kyoto University made investigation into the high energy (> 1.5 keV) response with fluorescence X-rays from the targets (Al, Cl, Ti, Fe, Zn, Se) and from the ⁵⁵Fe source.

3.2. Event Detection

For FI CCD data, we use the ASCA Grade method (see Figure 4) to detect X-ray events. In the case of XIS, we consider that most of the X-ray events don't split into a region larger than 2×2 pixels, and we then regard the events of Grade 0, 2, 3, 4, and 6 as the X-ray events. On the other hand, all of the events which split over the 2×2 pixels region are classified into Grade 7 and regarded as background events, because they are usually formed by the cosmic-ray. Here, the split threshold is the very important parameter for the Grade method, because the energy resolution and detection efficiency are very sensitive to the split threshold. For the XIS/FI, it is optimized to 20 ADU.

We also analyzed the BI data using the Grade method with the same split threshold to FI. Our calibration data shows, however, the imperfection of the original Grade method for the analysis of BI CCD.

3.3. Charge Trailing

First, we found peculiar non-uniformity of Grade branching ratio. Figure 5 shows the distributions of Grade 0 and



Horizontal Transfer

Figure 4. Top: Classification of ASCA Grade., Bottom: Definition of pixel name surrounding the center pixel of event (PH(E)).

Grade 2 events when the BI CCD was illuminated uniformly by X-rays of 8.6 keV. We can see that the event number of Grade 0 decreases with the number of vertical transfers in the imaging area. On the other hand, the event number of Grade 2 increases with the vertical transfer. Grade 2 events include two patterns.; the events split into PH(2) (see Figure 4 bottom) and split into PH(7), and only the latter contributes the increasing of the Grade 2 counts with the vertical transfer. This fact suggests a part of the charge of each event trails to a pixel opposite to the direction of the vertical transfer, and the amount of trailing charge increases in the charge transfer process. Similarly, some events which spread more widely, for example Grade 6 events, become Grade 7 by the charge trailing. As a result, these events which should be detected as X-ray events are classified into background events and abandoned. This phenomenon causes the reduction of the

detection efficiency. We therefore must quantify this effect and properly correct it.



Figure 5. Event number distributions of Grade 0 (circle) and Grade 2 (square). "Vertical" means the number of the vertical transfer in the imaging area.

We estimated the probability of charge trailing. The left of Figure 6 shows the correlation between the number of vertical transfers and the pulse height of PH(7) (shown as Q') extracted from Mn-K α events. Then we found Q' was proportional to the number of vertical transfers, and coefficient (*C*) was obtained as 6.3×10^{-3} by fitting with linear function. Here, we define the probability of charge trailing per pixel transfer as "Charge Trail Ratio", CTR. Then we can approximately estimate CTR with the equation;

$$CTR \left[1/Transfer \right] = C/Q, \tag{1}$$

where Q means the mean pulse height of the noticed events. For Mn-K α events, Q is ~1503 and CTR is estimated as 4.5×10^{-6} .



Figure 6. Left: Correlation between the number of the vertical transfer and the amount of the trailing charge. Q' means the pulse height of PH(7)., Right: The pulse height dependence of Charge Trail Ratio, CTR.

Furthermore, we found that CTR also depends on the energy of incident X-rays. We estimated CTR for Al- $K\alpha$ events, Cl- $K\alpha$ events, and Zn- $K\alpha$ events, similarly to Mn- $K\alpha$ events. Then the relation between the CTR and Q is given as the right of Figure 6, and it can be well fitted with the power-law model expressed as the solid line in the right of Figure 6. And the pulse height dependence of CTR is estimated as

CTR
$$[1/\text{Transfer}] = (1.72 \times 10^{-4}) \times Q^{-0.5}.$$
 (2)



Figure 7. Event number distributions of Grade 0, 2, 3, 4, and 6 (circle) and Grade 7 (square) before Charge Trail Correction and Grade 0, 2, 3, 4, and 6 after the correction (triangle) when the CCD was illuminated uniformly by Xrays of 8.6 keV.

With this result, we have developed a new analysis method, "Charge Trail Correction". First, we estimate the amount of the trailing charge of each event with equation 2, and we then correct the pulse height of PH(E) and PH(7); remove the trailing charge from PH(7) and add it to PH(E). Figure 7 shows the distributions of detected events (Grade 0, 2, 3, 4, and 6) and Grade 7 events before the correction and detected events after the correction. This result means a lot of Grade 7 events due to charge trailing are successfully reduced by the correction, and the distribution of detected events becomes uniform. Then the detection efficiency of a whole chip successfully improved about 10–20 percent.

3.4. Split Threshold Optimization

The second problem was that we found much worse energy resolution than the theoretically expected value. Table 1 compares the energy resolution of XIS/BI with that of XIS/FI. Thanks to the chemisorption process, the energy resolution of BI for high energy X-rays is comparable to that of FI. However the energy resolution becomes worse as incident X-ray energy becomes lower.

Table 1. Energy resolution of BI and FI, and the ratio of them. Both of them are analyzed with split threshold of 20 ADU.

Ex (keV)	BI (eV)	FI (eV)	Ratio (BI/FI)
0.28	57.0	33.1	1.72
0.53	63.0	42.2	1.49
4.51	129.0	114.1	1.13
8.63	170.7	159.0	1.07

As far as we use the Grade method, the charge split into surrounding pixels is not summed up unless the pulse heights of these pixels exceed the split threshold. In other word, if the pulse heights of split pixels are lower than the split threshold, these split components are ignored, and the energy resolution becomes worth as a result. The fact that the energy resolution is much worse than the expected value means that the split threshold is too large to detect such split charge. Therefore, split threshold should be optimized to be able to detect such split charge enough. In the case of the BI chip, furthermore, low energy events which are produced at far from the electrode are spread more widely than high energy events. Therefore, the degradation of energy resolution compared with the FI is notable especially in low energy band.

We then optimized the split threshold for the BI CCD. The left of Figure 8 shows the energy resolution and QE as a function of split threshold, where only O-K α events are used. Because of the reason mentioned above, the energy resolution becomes better as the split threshold becomes lower. However OE becomes lower, because the X-ray events classified as Grade 7 increase. Furthermore, the QE suddenly drop where the split threshold becomes lower than a certain value. We then determine the value which is a few ADU larger than those drop point as the split threshold. In the case of O-K α events, we choose 10 ADU as the split threshold. Then, energy resolution becomes \sim 55 eV which is better by \sim 13% than when the split threshold is 20 ADU (~63 eV). In addition, QE is lower by only $\sim 2\%$. Therefore, we can conclude that 10 ADU is better than 20 ADU as the split threshold. For high energy events, however, we found that 10 ADU is too low as split threshold. The right of Figure 8 shows the same relation as the left of Figure 8, in the case of Zn-K α events. We can see that the value where QE suddenly drops for Zn-K α is larger than that of O-K α . Therefore, if we choose 10 ADU as split threshold, the energy resolution becomes better by only $\sim 4\%$, but QE becomes lower by $\sim 6\%$. We then optimized the split threshold for Zn-K α events independently, and 13 ADU was chosen.



Figure 8. Left: The energy resolution (top) and QE (bottom) as a function of split threshold, where O-K α events are used., Right: The same relation but Zn-K α events are used.

We also optimized split threshold for other energy events and the results are shown in Figure 9. Because the optimum split threshold has energy dependence as shown in Figure 9, we decided to introduced a new Grade method with variable split threshold depending on the incident X-ray energy. The solid line in Figure 9 shows the bestfitted model for the relation between the optimum split



Figure 9. Variable split threshold for XIS/BI. The squares show the optimized split threshold at each energy, and solid line shows the best-fitted model.

threshold and X-ray energy. The function was given as

$$S [ADU] = 10.36 + 2.208 \log_{10}(E [keV]),$$
 (3)

where S and E mean split threshold and X-ray energy, respectively. In the BI analysis, we make Grade classification using variable split threshold according to equation 3. Of cause, we don't know the incident X-ray energy before analysis. We therefore once estimate the energy with temporary split threshold, and decide new split threshold with equation 3, we then calculate summed pulse height of the event using new split threshold.

We analyzed the data using the new Grade method with variable split threshold and the energy resolution is given as shown in Figure 10. Good energy resolution comparable to FI is achieved in the whole energy band of 0.2–13keV with the new method.



Figure 10. Energy resolution of BI (circle) and FI (square).

4. RESPONSE FUNCTION

Finally, we built the response function of XIS/BI using the ground calibration data analyzed with the new methods. Figure 11 shows the gain of BI CCD segment C. The relation between X-ray energy and pulse height is fitted with the linear function which has a break at the energy of Si-K edge (=1.838 keV). We then obtained the gain of 255.5 ch/keV for the energy band lower than 1.838 keV, and 255.2 keV for the energy band higher than 1.838 keV. The difference of the gain among the segments is less than 4%.



Figure 11. The energy scale linearity of XIS/BI.

In the case of XIS/BI, the response function is expressed with five component model; main peak, sub peak, Siescape peak, Si peak, and constant. The ratio of the intensities of these components depend on X-ray energy. Therefore, we estimated the relation between these ratio and X-ray energy, and determined the line profile for whole energy band. Figure 12 shows the spectra of O-K and Mn-K obtained by our ground calibration, and they are well fitted with the response function we built.

The gain, energy resolution, and line profile will change gradually on the orbit. However, we have already prepared the analysis software which is able to adjust the changes of the performance. We will renew the response function periodically with onboard calibration data and provide it for all users.

5. SUMMARY

We have reported the results of the ground calibration of XIS/BI CCD. The BI CCD has high quantum efficiency for low energy X-rays, and very good energy resolution was achieved by chemisorption process. We developed the new method, Charge Trail Correction and the new Grade method with variable split threshold, and then we successfully brought out the performance of the BI CCD. We built the response function with the ground calibration data and prepared the analysis software.



Figure 12. The XIS/BI spectrum of O-K line (left) and that of Mn-K line (right) fitted with response function built with the ground calibration data.

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CALIBRATION OF HEFT HARD X-RAY OPTICS

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ABSTRACT

Three hard X-ray telescopes (20-70 keV) have been produced for the High Energy Focusing Telescope (HEFT), a balloon-born mission. Each focusing, Wolter-I (conic approximation) optic was calibrated insitu using low-force surface metrology as they were being assembled and at the Danish National Space Center (DNSC) using a high-resolution 8 keV X-ray source after assembly. The first optic was also calibrated using 18-68 keV X-rays at the European Synchrotron Radiation Facility (ESRF). We have also fully illuminated a prototype optic using a UV source and compared the result with the above techniques. During instrument integration, a 25 keV X-ray source at a distance of 72 m was used to align the optics and confirm the expected effective area and imaging performance. The successful development of HEFT has lead to NuSTAR, a Small Explorer (SMEX) satellite mission. We discuss these pre-flight calibration methods used in the HEFT program.

1. INTRODUCTION

A new generation of hard X-ray instruments is required to open the hard X-ray frontier and answer fundamental questions about our Universe:

- How are black holes distributed through the cosmos, and how do they influence the formation of galaxies like our own?
- How were the elements that compose our bodies and the Earth forged in the explosions of massive stars?
- What powers the most extreme active galaxies?

We have developed thermally-formed glass substrates and a unique mounting technique to build the high performance, lightweight telescopes with large effective area to enable new discovery in the 6-80 keV energy band. Our approach is currently being flight demonstrated through the *High Energy Focusing Telescope (HEFT)*, a balloon born mission. Based on the success of *HEFT*, this approach will be used for the *Nuclear Spectroscopic Telescope Array* (*NuSTAR*), a small explorer class satellite. The *NuSTAR* mission will be the first satellite instrument to employ focusing optics in the 6 to 80 keV hard X-ray band. These optics, together with pixelized solid state detectors developed by Caltech, will make *NuSTAR* 1000 times more sensitive than previous experiments.

In this paper we summarize the optics production process and describe several pre-flight calibration methods used in the *HEFT* program. Much of this discussion is based on previous reports by Koglin et al. 2003-2004. We also describe the pre-flight alignment process for *HEFT*, give highlights from the 2005 flight and look to the future with *NuSTAR*.

2. OPTICS PRODUCTION

A major accomplishment of the *HEFT* program has been the successful development of thermally-formed glass optics with performance exceeding the HEFT requirements. We begin with thin glass, originally developed for flat panel displays, that is smooth and flat on all relevant length scales. Our approach is to thermally form these micro-sheets using standard quartz mandrels and commercially available ovens. We begin by placing a glass micro-sheet on top of a concave mandrel inside of the oven. As the oven is heated to the appropriate forming temperature, the glass begins to form into the mandrel under the influence of gravity. Just before the glass touches the mandrel surface, the forming process is terminated by lowering the oven temperature. In this way, near net shaped optic substrates are produced without perturbing the excellent initial X-ray properties of the glass micro-sheet, even without the aid of highly polished and very expensive mandrels.

The shells are characterized immediately after they are formed for quality control of the slumping process. An optical laser scanning apparatus designed and built at Columbia's Nevis Laboratory, is used to characterize free standing cylindrical substrates. From axial scan measurements at multiple azimuth positions, the cylindrical surface can be reconstructed using software to remove shell alignment errors. While the initial slumping parameters are roughly determined from the raw glass properties, the slumping parameters for each oven must be tuned for each new production setup (e.g., new forming mandrel radius or different glass type – AF45 or D263). This initial tuning generally takes several days, but after that, the ovens settings are normally quite stable and subsequent substrates are produced with consistent angular performance. In this way, it is only necessary to perform laser metrology periodically for quality assurance, and only small fine tuning adjustments are required over weeks of mass production slumping with the same setup.

After initial oven tuning, approximately 95% of the slumped shells were accepted for mounting for *HEFT*. Upon acceptance, the original 20 cm x ~120 degree pieces must be cut to the appropriate size -10 cm x ~70 degrees (i.e., a quint section) – using a scribe and break technique with better than 90% yield. The pieces are then packed and shipped to the Danish National Space Center (DNSC), where the substrates are coated with depth-graded W/Si multitilayers to providing good energy response extending to 70 keV (Jensen et al. 2003, Madsen et al. 2004).

Our unique mounting process involves constraining these coated mirror shells to precisely machined graphite spacers that run along the optical axis. In this process, the nominally cylindrical glass segments are forced to a conical form, and in the process, radial mismatches and some small twists in the glass are removed. In order to achieve large effective area, concentric layers of glass are stacked on top of each other starting with a titanium mandrel. Graphite spacers are first epoxied to the mandrel and then precisely machined to the correct radius and angle. Next, a layer of glass and second layer of spacers are epoxied to the first set of spacers. These spacers are then machined to the appropriate radius and angle. This process is repeated until the requisite number of layers is assembled. A key point of this process is that each layer of spacers is machined with respect to the optic axis and not the last layer of glass. In this way, there is never any stack-up error during the telescope fabrication.

Production of the first *HEFT* telescope HF1 began in May 2002 and was completed nine months later. Assembly of HF1 began using three spacers per quint section for the first 22 layers. At this point, a switch to five spacers per quint section was made. In order to make this change, an intermediate mandrel (which effectively replaced two layers) was added for structural support from which to build the subsequent 48 layers (70 layers total). The second *HEFT* flight module HF2, which was begun immediately after HF1 was completed, was assembled in a similar fashion over the next six months. For the third *HEFT* optic module, HF3, the innermost 12 layers were omitted and the entire optic (60 layers total) was built using five spacers over the course of the next five months. Both HF2 and HF3 were assembled at an average rate of \sim 3.5 layers per week. These three *HEFT* optic modules are pictured in Figure 1.



Figure 1: Three *HEFT* flight optics.

3. ANGULAR RESOLUTION

High-resolution X-ray measurements at 8.048 keV were performed on each optic at the DNSC X-ray calibration facility. A triple-axis diffractometer configuration utilized high-resolution, perfect channelcut monochromator and analyzer crystals - both Si(220) – in a non-dispersive configuration. The optic was first aligned optically so that it rotates about its axis with no visible wobble (less than $\sim 20^{\circ}$) in precisely aligned pinholes at each end of the optic module that define the optical axis. A photograph of the HF1 optic mounted for X-ray calibration is shown in Figure 2. The X-ray beam itself was then used to align the optic every ~30 degrees. To perform the alignment, the optic was rotated in the horizontal plane to determine the position of maximum X-ray intensity passing through the pinholes at the front and back ends of the optic. In this way, residual wobble from the mechanical alignment of the optic was removed.

It is important to emphasize that a Wolter-I optic is an imaging instrument. In this way, misalignment of the optic will not cause a displacement in the resulting image. The only consequence of any optic misalignment is that the measurements will be effectively performed at slight off-axis angles that vary as a function of azimuth position. The optic angular resolution is constant up to several arcminutes off-axis and only the throughput will be slightly degraded if the optic is slightly misaligned. Thus, small optic misalignments, estimated to be less than 15", will not effect the HPD measurements.

To perform the scattering measurements, the optic is translated into the X-ray beam, and the analyzer crystal is rotated to probe the angle of the scattered radiation. In this way, the conic approximation error inherent in the optic design is not measured. The analyzer crystal accepts 5" as a nearly perfect step function. By scanning the analyzer crystal, a histogram of the reflected X-rays in angle space is recorded. Due to the excellent crystal resolution, essentially no background exists in this measurement and only small systematic uncertainties (\sim 5") are associated with co-adding the individual scans. This metrology method is thus very simple to analyze and provides a very accurate composite two-bounce image of the upper and lower shells at multiple azimuth positions.



Figure 2: End view of the first *HEFT* optic (HF1) in 8 keV X-ray facility.

The BM05 beamline at the ESRF synchrotron facility was used to perform high energy X-ray measurements on the HF1 optic. A double bounce Si(111) monochromator and beam collimators were used to generate an in-plane divergence of 1" for the X-ray beam. The monochromator has an energy range of 15 to 70 keV. The alignment of the optic was performed similarly to the DNSC setup, and as with the 8 keV measurements, pencil beam scans were performed.

For HF1, a CCD detector was used at ESRF to generate a spatial image instead of using an analyzer crystal to measure the angular distribution of the focused X-rays. Due to space constraints, the CCD detector could not be placed at the focal point of the optic located 6000 mm from the optic center, but instead was positioned 2457 mm from the optic center. The only consequence of the shorter effective focal distance is an increase in the conic-approximation error folded into the image. However, this error is still never more than ~20", and a small correction (~3") is applied to correct for its impact upon the performance of these shells.

Unlike the scanning technique of the 8 keV measurements, a significant amount of background is measured using this imaging technique. While this background is normally quite flat, it does begin to have structure once the total measurement throughput becomes low. However, a background subtraction

procedure has been developed to deal with this problem and is discussed in more detail elsewhere (Koglin et al. 2004a). The systematic uncertainty in these high-energy X-ray measurements is estimated to be $\sim 10\%$.

In a later measurement of a prototype optic for *NuSTAR*, we performed high energy measurements at ESRF using the technique of scanning with an analyzer crystal that was described for the 8 keV measurements at DNSC (Koglin et al. 2004b). While this provides for a more precise measurement of the angular resolution (i.e., zero background), it is also significantly more time consuming (~15×) than direct imaging with a CCD. Due to the limited availability of beamtime at ESRF, it is not a practical method for calibrating large optics at multiple energies.

Both 8 keV and high energy (18-68 keV) X-ray calibration data have been previously reported for HF1 in addition to LVDT metrology. The images obtained from these methods are plotted in Figure 3.



Figure 3: An image generated using a ray-trace code with LVDT surface metrology data is plotted in a). Composite images generated from 8, 40, and 50 keV pencil beam scans are plotted in b), c) and d), respectively.

Each independent measurement yielded consistent results, and the HPD performance of the complete optic was determined to be 1.3 ± 0.1 ' at 40 keV (Koglin et al. 2004a). A clear improvement in performance was measured after changing from three to five spacers per quint section. The pre-mounted, free-standing

mirrors are only nominally cylindrical with small radial mismatches and twists. The improvement in performance with greater spacer density results from the greater ability to remove out-of-phase roundness errors in the mirrors (i.e., twists such that the nominal graze angle in the mirror changes with azimuth angle). The goal of the mounting method is not to improve the axial figure of the mirrors - the goal is to simply constrain the mirror to the correct radius and angle at the point of the graphite spacers. Away from the spacers, the intrinsic roundness errors in the mirrors will cause the nominal graze angle of the mirror to deviate slightly from the required graze. By increasing the spacer density, this type of error can be minimized. The HF2 and HF3 optics have also been calibrated with LVDT and 8 keV measurements using the same procedures, the results of which have been previously reported (Koglin et al. 2004b).

We have previously conducted a ultra-violet (UV) full illumination test of a prototype optic at the University of Colorado's Center for Astrophysics and Space Astronomy (CASA) using their 'long-beam' vacuum tank illustrated in Figure 4. The UV source originates through a 100 µm diameter pin-hole. The source UV radiation is then reflected onto a parabolic mirror at one end of the tank by a collimating mirror. The parabolic mirror floods the vacuum tank with UV radiation directed parallel (<10") along optical axis of the tank. Since the 6 m focal length of the test optic was longer than the usable length of the vacuum tank, the optic was positioned 3 m from the end opposite the parabolic mirror, and a gold folding mirror was used to reflect the UV radiation focused by the optic back onto a micro-channel plate (MCP) detector. The MCP detector, which was built by Siegmund Scientific, has a sensitive area of 255 mm² with 85 µm resolution and operates with a quantum efficiency of about 5%. A sheet of Teflon with an opening for the optic was positioned in front of the optic and MCP to shield the MCP from background UV radiation.



Figure 4: Illustration of UV test setup at CASA.

While this method provides no detailed information on the individual optic components, it unambiguously provides a 'what you see is what you get' result for the image requiring essentially no intermediate data analysis steps. Once the time consuming task of setting up the test hardware was completed, we were able to quickly perform both off-axis and depth of focus studies to gain a more complete understanding of the optic performance. These measurements were consistent with the expected optic response, and the results agreed well with both LVDT and 8 keV X-ray. The good agreement between the X-ray and UV measurements indicate that no difficulties exist in properly aligning the optic for the X-ray pencil beam scans. A more detailed discussion of this measurement is given by Koglin et al. (2003).

4. EFFECTIVE AREA

A highly nested optic is required to achieve large effective area, part of which will inevitably be obscured by structural support. Past soft X-ray telescopes using segmented focusing optics have reported significant losses stemming from geometric factors such as shadowing due to mirror misalignments, but these losses have not always been completely understood - e.g., SODART (Christensen et al. 1997), ASCA (Tsusaka et al. 1995), Astro-E (Shibata et al. 2001). In the case of HEFT and other similar hard X-ray optics, shadowing becomes especially important due to the smaller graze angles required for hard X-rays. The *HEFT* assembly approach is particularly adept at minimizing such shadowing because each mirror segment is constrained by several spacers machined to the correct radius. However, there will typically be an in-phase roundness error associated with these mirrors as they become slightly displaced between spacers due to radial mismatch (the shells are nominally cylindrical but mounted to a conic geometry), which will cause some shadowing. Losses from shadowing in this manner will be considered to be loss in axial throughput - in contrast to losses from structural obscuration that will be dealt with later.

In addition to assessing the angular performance, the LVDT data was used to determine the axial throughput using raytrace calculations. The result of these throughput calculations are shown in Figure 5. We have also determined the axial throughput at DNSC using 8 keV scattering measurements in a double-axis diffractometer configuration without the analyzer crystal in place. For these measurements, the 8 keV X-ray flux was measured every 2.5 degrees with a pin diode detector and calibrated with the direct beam similarly to the performance measurements. The axial throughput results extracted from this 8 keV data are also plotted in Figure 5 along with an analytic approximation to the 8 keV and LVDT.

For the first 22 inner mandrel layers where only three spacers were used for each mirror segment, the axial

throughput becomes increasingly degraded as the conic angle decreases toward the innermost layer. This trend is expected because a given roundness error will cause a relatively longer shadow for shallower graze angles than the same error will cause for larger graze angles. After the switch to five spacers starting at layer 25, the axial throughput was consistently ~90%. Because of the good agreement between the LVDT simulation and the 8 keV X-ray illumination measurements, we can be confident that the loss in axial throughput is completely accounted for by geometric shadowing effects. Any degradation in throughput due to other factors such as scattering from dust particles or imperfections in the multilayer coatings must be minimal, as is indeed expected.



Figure 5: HF1 throughput determined from raytrace calculations using LVDT data and measured directly using 8 keV X-rays. The 8 keV measurements are the average for the entire layer as are the LVDT measurements for the inner layers up to layer 16. The rest of the LVDT measurements are typically only for one sample quint segment. The errors in each of these measurements are estimated to <5%.

Each *HEFT* optic module was mounted on the gondola using a support structure similar to that shown in Figure 2 that will cover the gaps between quint sections. The five supports will each be $w_{gap} = 3 \text{ mm}$ wide – about the same width as the gap between quint sections. While the spacers themselves are only 1.6 mm wide, a small amount of epoxy excess around the spacer will cause added obscuration for each spacer. On average, each spacer obscures $w_{spacer} \cong 2.5 \text{ mm}$ of the segment. Thus, the total obscuration will be

$$\varepsilon_{\text{obscuration}} = (n_{\text{spacers}} w_{\text{spacer}} - n_{\text{segments}} w_{\text{gap}}) / (2\pi r_{\text{uo}}), \quad (2)$$

where $n_{spacers}$ is the number of spacers, $n_{segments} = 5$ is the number of mirror segments, and r_{uo} is the middle radius of the upper layer. The total obscuration for the first two *HEFT* modules will range from 10-20%.

5. HEFT PRE-FLIGHT OPTICS ALIGNMENT

The three flight optics for HEFT were co-aligned to focus on their respective CdZnTe detectors using an Xray source. An alignment fixture was positioned using laser alignment at a distance of 72±0.05 m from the optic entrance. The X-ray source was installed and conditioned in the first optic position. The x-ray generator was operated at a current of 0.30 mA and a voltage of 35 kV. The mean energy of the X-ray source at the optic aperture was approximately 25 keV with a spread of about ± 4 keV. A aperture on the x-ray tube was adjusted to center the source flux at the entrance of the optic using a NaI detector with crystal diameter of 5.0 cm. The X-ray source produced a flux intensity distribution that was measured to be uniform within better than 20% over a diameter greater than 50 cm (much larger than the optic diameter of 24 cm)



Figure 6: Images obtained from a 25 keV source positioned 72 m from the HF1, HF2 and HF3 optics are plotted in a), b) and c), respectively. Simulations for this setup with off-axis sources (i.e., optic misalignments) of 0', 1' and 2' are plotted in d), e) and f), respectively. Pixel sizes are 0.5 mm \times 0.5 mm (17" \times 17").

A raytrace simulation was performed for 25 keV Xrays to determine the expected image topology for onand off-axis sources (or alternatively a misalignment of the optic for an on-axis source), in addition to the expected effective area for a source positioned at 72 m instead of infinity. This simulation included obscuration from spacers and structural obscuration (c.f., Eq. 2), a throughput model based on the measurements shown in Figure 5, and the expected W/Si multilayer response. The simulation also accounts for mirror imperfections using Beckmann scattering theory, with the model parameters (e.g., amplitude and spatial frequency of the errors) adjusted to match the observed response. The simulated images for 0', 1' and 2' off-axis are shown in Figures 5 d, e and f, respectively.

X-ray alignment was performed iteratively by acquiring an X-ray image, comparing it to these simulations and determining how far, and in which direction, the optics needed to be adjusted. This process was repeated for each of the three optics, two of which required adjustments between 1' to 2'. The resulting images for HF1, HF2 and HF3 are shown in Figures 5 a, b and c, respectively. Based on the relative symmetry of these measured images compared to the simulated images, the telescopes appear to all be co-aligned to within at approximately 1'. The effective area was determined from the ratio of the count rate at the detector and the flux density at the optic entrance with a correction factor of α =0.687 for X-ray attenuation over the intervening 6.2 m path, and is given by

$$A_{\text{meas}} = R_{\text{FP}} / (\text{Flux} \times \alpha).$$
(3)

The measured data and the theoretical effective area A_{theory} are detailed in Table 1. The measured effective area is found to be within 20% of the value expected (with an estimated uncertainty in the measurements of 20% due to source non-uniformity and 10% in the simulations mainly due to uncertainty in approximating X-ray source energy distribution, ~21-29 keV, with a delta function at 25 keV). These effective area measurements, as well as the X-ray images, confirm that the optics were performing as expected.

Table 1: Pre-flight effective area measurements

Optic	Flux	R _{FP}	A _{meas}	Atheory
	ph/cm ² /s	ph/s	cm^2	cm^2
HF 1	13.9	189	20	25
HF 2	12.2	190	23	25
HF 3	12.9	160	18	20

6. HEFT FLIGHT

HEFT was launched from Ft. Sumner, NM on May 18, 2005 at 19:55 UTC. Photographs of the *HEFT* gondola and balloon just minutes before and after launch are shown in Figure 7. The flight was terminated at 20:40 UTC the following day. Observations of Her-X1, Cyg-X1, GRS 1915, 3C454.3, X-Per, and the Crab Nebula were performed over this time. We are currently processing the data and expect to publish results in the near future.



Figure 7: Photographs of *HEFT* minutes before and after launch on May 18, 2005 in Ft. Sumner, NM

7. NUSTAR

NuSTAR is a small explorer mission currently in an extended Phase A study period. A decision on proceeding to development is expected in early 2006 with a nominal launch date of 2009. The optics design and production process proposed for *NuSTAR* is based on *HEFT* (Koglin et al. 2004b and 2005). The extensive design heritage, calibration techniques and lessons learned from *HEFT* will be employed for *NuSTAR*. For example, smaller mirror segments with more spacers will be used to improve the angular resolution (40") and throughput for *NuSTAR*.

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XMM-EPIC TIMING MONITORING AT ESAC

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ABSTRACT

The EPIC-pn camera on board XMM-Newton provides a very high time resolution. In its Timing mode, EPIC-pn reaches a time resolution of 0.03 ms and 7 μ s in the Burst mode. In order to monitor the relative timing accuracy, XMM-Newton performs two observations a year of the Crab pulsar. An automatic tool has been created to check the timing accuracy of EPIC-pn. It calculates the period of the Crab pulsar in the X-ray regime and compares it with the period obtained from radio data. Observations of pulsars PSRB0540-69, PSRB1509-58 and PSRB1055-52 have also been used in this analysis. We present first results of the timing accuracy from this analysis covering the whole XMM-Newton mission time till revolution 1000.

Key words: XMM-Newton; EPIC-pn; calibration; timing.

1. INTRODUCTION

The EPIC instruments on board XMM-Newton were succesfully launched on 1999 December 10. EPIC provides spatially resolved spectroscopy over a field of view of 30' with moderate energy resolution. The EPIC-pn camera is equipped with a p-n-junction CCD that has been specially developed for XMM-Newton. EPIC-pn can be operated in different readout modes, four imaging modes and two fast readout modes (Timing and Burst modes). We concentrate here on the timing capabilities of the EPIC-pn camera. For a detailed description of EPIC-pn see Kirsch et al. 2001, Kuster et al. 2001, Ehle et al. 2005.

2. TIMING MONITORING

The relative timing accuracy is monitored by calculating the X-ray period P_X of a pulsar and comparing it with the period P_R obtained at radio frequencies. The relative error gives the timing accuracy (Eq.1)

$$\frac{\Delta P}{P} = \frac{P_R - P_X}{P_R} \tag{1}$$

XMM-Newton performs one observation of the Crab in autumn and one in spring, at different position angles, in order to monitor the timing accuracy. The relative timing accuracy has also been checked with XMM-Newton observations of pulsars PSRB0540-69, PSRB1509-58 and PSRB1055-52.

3. OBSERVATIONS AND PROCESSING OF DATA

This analysis was performed using Crab observations made in revolutions 0056, 0411, 0698 and 0700 in Timing mode, and 0411, 0234, 0874 and 0955 in Burst mode. PSRB0540-69 was observed in revolution 0085 (Timing mode), PSRB1509-58 in revolution 0137 (Timing mode) and PSRB1055-52 in revolution 0187 (Timing mode). Data was analysed using the SAS version 6.5.0. A barycentric correction of photon arrival times was performed using the SAS task *barycen*.

4. PERIOD DETERMINATION

4.1. Radio period of pulsars

Radio data for the Crab pulsar was obtained from the Jodrell Bank Observatory (University of Manchester) where one observation of the Crab is performed every month (Lyne et al. 2001). For the other pulsars data was obtained from the Princeton pulsar database (Taylor et al. 1993). The radio period for the epoch of the X-ray observation is obtained by a linear interpolation in the case of the Crab pulsar, and by extrapolating the data for the other pulsars using \dot{P} and \ddot{P} .

4.2. X-ray period of pulsars

The X-ray period is obtained by folding the light curve of the pulsar over a range of test periods, using as a first trial the radio period. For each observation a χ^2 maximization test is performed. Fig. 1 shows the resulting χ^2 distributions for the four pulsars. The FWHM of these



Figure 1. Different χ^2 distributions for the different pulsars used

 χ^2 distributions, approximating it by an isosceles triangle, is $FWHM \simeq \frac{P^2}{T}$, where P is the period and T the time span. We calculated the FWHM for all four pulsars and compared them with the expected values, and those values agree.

5. RESULTS

The relative timing accuracy obtained for the Crab is $\frac{\Delta P}{P} < 3x10^{-8}$. This can be seen in Fig. 2. In order to improve statistics and to create additional data points, we merged all obervations from revolutions 0411,0700 and 0955 and analysed those as separate data files. Table 1

Table 1. Relative timing accuracy obtained for all pulsars

	$\frac{\Delta P}{P}$
Crab (all obs.)	$<3x10^{-8}$
PSRB0540-69	-4.0×10^{-6}
PSRB1055-52	2.3×10^{-7}
PSRB1509-58	-1.4×10^{-5}

and Fig. 3 show the relative timing accuracy obtained for all four pulsars.

The relative timing accuracy obtained for pulsars PSRB0540-69 and PSRB1509-58 is worse than expected.



Figure 2. $\frac{\Delta P}{P}$ vs. epoch for all Crab observations. Allows to check the relative timing accuracy along the mission

Future observations of those pulsars are planned, in parallel with RXTE and radio observations, in order to verify the relative timing accuracy.



Figure 3. $\frac{\Delta P}{P}$ *vs. epoch for all four pulsars*

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ABSTRACT

The XMM-Newton satellite is the most sensitive X-ray observatory flown to date due to the great collecting area of its mirrors coupled with the high quantum efficiency of the EPIC detectors. It performs slewing manoeuvers between observation targets tracking almost circular orbits through the ecliptic poles due to the Sun constraint. Slews are made with the EPIC cameras open and the other instruments closed, operating with the observing mode set to the one of the previous pointed observation and the medium filter in place.

Slew observations from the EPIC-pn camera in FF, eFF and LW modes provide data, resulting in a maximum of 15 seconds of on-source time. These data can be used to give a uniform survey of the X-ray sky, at great sensitivity in the hard band compared with other X-ray all-sky surveys.

Key words: X-rays, XMM-Newton, slew, survey.

1. INTRODUCTION

XMM-Newton traces slewing paths over the sky while manoeuvering with both EPIC-pn and EPIC-MOS cameras open. Data from slew observations are recorded into Slew Data Files (SDF), which have been stored in the XMM-Newton Science Archive (XSA) from revolution 314. Not all these data are scientifically useful and data from the EPIC-MOS cameras are now used for calibration purposes.

This paper describes the EPIC-pn slew data processing strategy, used to give a uniform coverage over the sky, in order to create the first catalogue of slew detections with XMM-Newton (Freyberg et al., 2005). It also reports on the current status and scientific utility of the survey.

2. OBSERVATIONS AND DATA ANALYSIS

The optimum source searching strategy derived for slew data processing (Read et al., 2005; Saxton et al., 2005) is described below. The attitude reconstruction and spurious detections are dealt with in the corresponding subsections.

Data from the EPIC-pn camera are only used due to the faster readout in its observing modes and its high effective area with respect to the EPIC-MOS cameras. In particular, only FF, eFF and LW modes are used because the other EPIC-pn modes are not appropiate for source determination. The characteristic low background of the observations (average 0.1 cts/arcmin²) and the tight PSF of the telescopes provide good sensitivity to detect extended sources (Lazaro et al., 2005). Nevertheless, slews performed at times of enhanced solar activity have been rejected in the current processing although they are hoped to be included in the future. Slew observations are divided into ~ 1 square degree event files before processing in order to get accurate positions over the sky. A near standard pipeline eboxdetect/emldetect tuned for \sim zero background was performed on images containing only single events (pattern 0) in the 0.2-0.5 keV energy range and single plus double events (patterns 0-4) in the 0.5-12 keV band. Three different energy bands are source searched independently: total band (0.2-0.5 keV), soft band (0.2-2 keV) and hard band (2-12 keV).

2.1. Attitude reconstruction

The attitude reconstruction is crucial in the determination of source coordinates. After further investigation we concluded that during slews an attitude reconstruction slightly different than for pointed observations had to be performed. The optimal attitude file for reconstructing the astrometry in slew observations is the Raw Attitude File (RAF) with 0.75 seconds subtracted from every entry, a timing error that is due to a delay of the star tracker CCDs.



Figure 1. Aitoff projection of the distribution of all XMMSL1 detections in the total band.

2.2. Spurious detections

Systematic effects in the instrument and detection software lead to a number of spurious detections that are outlined below. In the current slew pipeline unreal sources due to optical loading and detector flashes are directly rejected during processing by using only single-pixel events (pattern 0) below 0.5 keV.

False detection: detections not verified through visual inspection. Within bright and/or extended source: multiple detections of the same object. Position suspect: sources located at the edge of an image and others. Background related: sources positioned in localised flared images.

3. THE XMM-NEWTON SLEW CATALOGUE

Images and exposure maps have been source searched for 219 slew observations producing 4179 detections in the total band (Fig. 1), 2750 in the soft band and 844 in the hard band. The number of real sources is under investigation as spurious detections are currently being flagged. The sky coverage is ~ 6300 square degrees which means $\sim 15\%$ of the whole sky, indicating a source density of about 0.65 sources per square degree.

In order to check the quality of our detections we correlated the 2178 non-extended sources with det_ml>10 (sigma 3.9) with different catalogues. It was found that $\sim 56\%$ of the sources have a RASS counterpart within 60 arcsec, with 68% of matches lying within 15 arcsec. Furthermore, correlations with the astronomical database SIMBAD show that 68% of the matches lie within 8 arcsec. These correlations also indicate a great variety of detected objects during slews, including AGN, galaxies, cluster of galaxies, LMXB and SNR among others.



Figure 2. Flux limits of the X-ray large area surveys. Fluxes for the XMM-slew survey have been calculated for a source with det_ml=10 and passing through the centre of the field of view. These fluxes were derived from count rates based on energy conversion factors assuming an absorbed power-law model with $N_H = 3.0 \times 10^{20}$ cm² and slope 1.7

The sensitivity of the survey in the different bands was obtained and flux limits at det_ml of 10(8) were compared with those of other X-ray all-sky surveys (Fig. 2). The soft X-ray band detection limit is $6(4.5) \times 10^{-13} \ erg \ s^{-1} \ cm^{-2}$, comparable to the one of the ROSAT bright source catalogue (Voges et al., 1999). The sensitivity of slew detections is particularly evident for the hard X-ray band whose limit is the deepest ever $4(3) \times 10^{-12} \ erg \ s^{-1} \ cm^{-2}$ (ten times deeper than EXOSAT, HEAO-1).

All detected sources will comprise the first XMM-Newton catalogue derived from slew observations, the XMM-Newton Slew 1 (XMMSL1). It is expected to be published by the end of 2005 and updated when more slews are available to finally have an all-sky survey.

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MONITORING OF THE EPIC CAMERAS AT THE XMM-NEWTON SCIENCE OPERATIONS CENTRE

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ABSTRACT

The XMM-Newton Science Operations Centre (XMM-SOC) at the European Space Astronomy Centre (ESAC) near Madrid/Spain currently operates three scientific instruments on board XMM-Newton. This includes also scientific monitoring of the instruments concerning their stability and health. One of the main instruments onboard XMM-Newton is the European Photon Imaging Camera (EPIC). Main targets of the monitoring are i.e. the behaviour of the Charge Transfer Efficiency (CTE), the gain, the effective area or the bad/hot/noisy pixels. The monitoring is performed by combination of calibration observations with an internal radioactive calibration source and observations of astronomical targets. We describe software tools that search for useful internal calibration data and perform the monitoring. Also we show some examples of the monitoring material available at the XMM-Newton web site.

1. THE XMM-NEWTON EPIC CAMERAS

XMM-Newton¹ was launched in December 1999 on an Ariane 504 rocket from French Guyana. Three Wolter type-1 telescopes with 58 nested mirror shells focus Xray photons onto the five X-ray instruments comprising the European Photon Imaging^{2,3} Camera (EPIC) and the Reflecting Grating Spectrometers⁴ (RGS). The Optical Monitor⁵ (OM), employing a 30 cm Ritchey Chrétien optical telescope, can perform parallel optical observations of the same field. EPIC is comprised of three cameras employing two distinct detector technologies. The two EPIC-MOS cameras use front illuminated EPIC-MOS (Metal-Oxide Semi-conductor) CCDs as X-ray detectors, while the EPIC-pn camera is equipped with an EPIC-pn (p-n-junction) CCD. Both have been specially developed for XMM-Newton. EPIC provides spatially resolved spectroscopy over a field-of-view of 30' with moderate energy resolution.

2. MONITOR FLOW

The monitoring is performed by a combination of calibration observations with an internal radioactive calibration source and observations of astronomical targets. The offline monitoring is realized through the monitoring of the measured energies and widths of the internal calibration source lines, which are performed with the filter wheel in closed filter position allowing in addition a radioactive Fe-55 source that produces Mn-K and Al-K characterstic lines to shine on the CCD. This is called a CalClosed measurement. Tools were developed to support the trend analysis of parameters, which affect instrument performance and health largely automatic.

3. STANDARD CALCLOSED MESUREMENTS The collection of CalClosed exposures has been automated by software. The software searches the XMM-Newton Science Archive (XSA) for CalClosed obser-



Figure 1: Spectrum of the internal radioactive calibration source in revolution 80 (black) and revolution 998 (red). Note that the calibration source is getting fainter.

vations, collects them, extracts the needed files and provides them on a central repository for further processing by the instrument team. In the past dedicated CalClosed measurements have been performed in order to sample the performance of the cameras around every 7-10 revolutions. This frequency is necessary to sample sufficiently the behaviour of the MOS-CTE degradation (see Fig. 2).

4. THE USE OF SLEW CALCLOSED DATA

However, since the calibration source is decaying exponentially the required observation time increased significantly. Analysing data that are taken by XMM-Newton in Medium filter position slewing from one target to the next it turned out that those data are only of scientific use for the EPIC-pn camera.⁶As of revolution 918 it was therefore decided to perform EPIC-MOS slew measurements in CalClosed to gain more calibration data. The dedicated CalClosed measurements have from there on been stopped. For the EPIC-pn camera CalClosed observations will now only be performed during the RGS/OM calibration observa-

tions that are not useful as astronomical targets for the EPIC-pn calibration approximately every 2-3 month. This approach saves about 2% exposure time for scientific observations. The EPIC-MOS cameras will of course also use those observations. In order to derive CTE values sufficient statistic needs to be accumulated in a CalClosed measurement. This is not given in one slew data set and therefore software has been developed to merge a number of slew CalClosed datasets to derive from that the CTE parameters. This approach naturally reflects always a trade-off between accuracy in CTE parameters and accuracy in time behaviour since the accumulation of data over time smears out the CTE evolution. The current approach provides a data point every 10 revolutions. We approximated the sample frequency for calibration measurements with time taking a 10 ksec baseline at revolution 1 and an average slew time per revolution of about 4,26 ksec. (see Fig.2)



Figure 2: Required sampling period [in rev] of slew CalClosed exposures for CTE measurement as function of revolution

5. MONITORING EXAMPLES

It is known that harsh radiation conditions may induce the formation of electron traps in the detectors, thus degrading the CTE. Fig. 3 shows the evolution of the CTE for the different EPIC cameras. Solar flares created a series of jumps in the CTE of the EPIC-MOS cameras prior to their operation at a lower temperature, while the EPIC-pn CTE degrades independently of solar flares at a nearly constant rate per year.

By the term "bad" or "hot" pixel we mean any pixel within a CCD exhibiting abnormal behaviour which makes it useless for scientific data collection due to its tendency to mimic a signal (hot) or to yield no signal (bad). The number and location of hot pixels has to be monitored in order to flag pixels which have to be masked to reduce loading of the spacecraft telemetry budget, or because they adversely affect science quality. For the EPIC-MOS cameras the number of hot pixels increased through the mission due to micrometeoroid events⁷ and due to aging caused by hard radiation particles. Figure 4 shows the evolution of hot pixels for CCD2 in EPIC-MOS2.



Figure 3: Evolution of the CTE of the EPIC camera CCDs for the energies of the internal calibration source at Mn-K, 5896 eV, (blue crosses) and Al-K, 1486 eV (red triangles). Upper panel: EPIC-MOS, Lower panel EPIC-pn. The different blue and red tones in the upper panel of the figure represent the EPIC-MOS1 (light blue (Mn), orange (Al)) and EPIC-MOS2 (dark blue (Mn), red (Al)). The discontinuity around rev.533 is related to the cooling of the **EPIC-MOS** cameras



Figure 4 Hot pixel evolution of EPIC-MOS2 CCD2. The diamonds show the absolute number of hot pixels. The crosses show the number of hot pixels that are not yet masked out on board (candidate hot pixels). The green lines indicate an update of the onboard bad pixel table that masks out hot pixels. Note that after the cooling in rev 533 most of the hot pixels have disappeared and the onboard bad pixel table could be relaxed to a few pixels per CCD.

6. CONCLUSION

By the time of this conference in September 2005 we can provide with our current approach of CalClosed data acquisition one data point about every 10 revolution to measure the CTE behaviour of the EPIC-MOS cameras. The monitoring sampling frequency will slow down however up to a point where depending on the future structure of CTE changes we may have to perform in addition to the slew CalClosed again dedicated CalClosed observation in order to maintain a satisfying monitoring sampling frequency.

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NOVEL APPROACHES IN TECHNOLOGIES FOR LARGE LIGHT-WEIGHT X-RAY SPACE TELESCOPES

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ABSTRACT

The future large X–ray astrophysics space missions (such as the ESA XEUS) require very light-weight but large and precise X-ray mirror shells. This trend is general since the scientific need is to achieve better sensitivity at very high angular resolution. Clearly, the developments of completely innovative techniques and approaches are necessary. We describe and discuss the possible alternative techniques. They include Si wafers shaping, thin glass technology and glass thermal forming, as well as glossy metals and glossy carbon.

Key words: X-ray telescopes, X-ray optics.

1. INTRODUCTION

Imaging X–ray mirrors represent a key component of X– ray astrophysics missions. Various technologies for their production exist, the most important ones being the galvanoplastic replication and the direct polishing of the mirror shells. The future X-ray astrophysics missions such as the ESA's XEUS (Aschenbach et al. 2001) will however require innovative technologies and approaches resulting in lighter mirror shells in order to achieve high sensitivity and high angular resolutions at a still reasonable weight of the mirror assembly (Hudec et al. 2004, 2005).

2. GLASS AND GLASS THERMAL FORMING

Glass has 4 times less volume density if compared with nickel in common use. Highly flat and highly smooth thin glass foils may serve in various future experiments. Glass foils for the X-ray optics can be used either as flat or curved, while the curved foils can be either bent (without heat) or thermally shaped. Bent glass foil optics has been already successfully used for a test laboratory sample for a XEUS-like optics module (the 0.75 mm thick and 300 x 300 mm large glass foils were beent to achieve the required parabolic profile). Here we report on the project supported by the Ministry of Industry and Trade of the Czech Republic and focusing on thermal glass forming. We also report on the first preliminary results obtained within this project. The thermal forming of glass is not a new technology since it has been used in various regions of glass industry and glass art as well as in production of Cerenkov mirrors. However, the application of this technology in X-ray optics is related with the need to significantly improve the accuracy and minimize the errors. As a first step, small (10 x 5 cm, 0.75 mm thick) glass samples of various types provided by various manufacturers have been used and thermally shaped. The geometry was either flat or curved (cylindrical). The project continues with larger samples (recently 300 x 300 mm) and further profiles (spherical and parabola). Although we focus on curved shells since the main goal is to develop a technology meeting the requirements of the large future X-ray telescopes with Wolter geometry, the replication of flat foils represent another important application since this approach is expected to improve the flatness of X-ray flats (foils) needed e.g. for Lobster Schmidt lenses.

The small glass samples were thermally formed at the Center for Advanced X-ray Technologies, Reflex, Prague, as well as at the Institute of Chemical Technology in Prague. For large samples (more than 300 mm), we expect to use the thermal glass forming device available at the Compas Co. in Turnov as well as their expertise in thermal shaping of large (diameter 0.5 to 1 m) glass Cerenkov mirrors (spherical surfaces). Already for these tests, our idea is to develop technology suitable for mass and inexpensive production of thin X-ray optics shells. This means that we avoid expensive mandrels and techniques not suitable for mass production or too expensive. Numerous glass samples have been shaped and tested. The shapes and profiles of both mandrels as well as the resulting glass replicas have been carefully measured by metrology devices. The preliminary results show that the quality of the technology process and resulting quality of the thermal glass replica can be significantly improved by the optimisation of the material and design of the mandrel, by the modification of the thermal forming process, as well as by the optimisation of the temperature. After the (partly significant) modifications and improvements we have obtained the resulting deviation of the thermally formed glass foil from the ideal designed profile less than 1 micron (peak to valley value). This value is however strongly dependent on the exact temperature as well as on other parameters, so we believe that a significant further improvements are possible. The fine original microroughnes (typically better than 1 nm) of the original float glass foil has found not to be degraded by the thermal forming process.

3. SI WAFERS

Another alternative recently considered as one of most promising, is the use of X-ray optics based on commercially available silicon wafers manufactured for purposes of semiconductor industry. Silicon is relatively light (volume density 2.3) and already during the manufacture process is lapped and polished (either on one or on both sides) to very fine smoothness (better than 0.1 nm) and thickness homogenity (of order of 1 micron). We have created a collaboration in the Czech Republic to study and to exploit the high precision X-ray optics based on Si wafers. For the tests, Si wafers developed and produced by the ON Semiconductor Company in the Czech Republic as well as by other Czech manufacturers have been used. Various techniques and approaches how to shape the Si wafers to fine and accurate optical surfaces have been exploited. This is not trivial since Si wafers are difficult to shape. The results are promising and justify the continuation of these efforts. Our recent goal is to achieve very high accuracies in shape while maintaining the fine surface microroughness and to minimise the internal stress which is necessary for the high precision and for the very long lifetime of the space telescope.

4. AMORPHOUS-GLASSY METALS AND GLASSY CARBON

The metallic amorphous alloys have very interesting physical properties. Mechanical properties of amorphous alloys are comparable with those of high strength steel. As an example, the mechanical properties of amorphous Ni/Fe alloy are nearly four times better than those of crystalline Ni.

The another promising alternative is the glassy carbon. The glass-like carbons have bulk densities around 1.5 g cm⁻³ (although they can be as small as 1.4 g cm⁻³)

and even 0.6 g cm⁻³ if an extended porosity may be accepted) which are almost equal to those of the conventional synthetic graphite and lower than any previous material considered for future large area X-ray mirrors. The glossy carbons with high porosity can even reach bulk densities of 0.6 g cm $^{-3}$. The beending strength of glass like carbons amounts to 50-200 MPa, the Young's modulus to 20-32 GPa, and the C.T.E. amounts to about 1 x 10^{-6} C⁻¹. Glass like carbons are hard materials as shown by their shore hardness of 100, and of 70-80 after graphitization. However, they have little mechanical shock resistance and belongs to typical fragile materials. This can be, on the other hand, affected by the selection of a suitable filler. They exhibit low self-lubricity and high abrasion resistance reflecting their special structures, compared with conventional graphite. The applications of glass-like carbons have been rather limited for the past few dozens of years. It is just recently that they have attracted much more interest in terms of industrial applications. Among the parameters, the glass like carbons seems to be favourable because of their low density and low thermal expansion. The large-size composite glass-like carbon thin plates have been already successfully produced for fuel cell separators (Marsch et al. 1997).

5. CONCLUSION

There are several promising alternative methods to produce large precise and lightweight X-ray mirror shells for future X-ray astronomy satellite missions. The first prototypes and tests have indicated that the thermally formed glass foils and shaped Si wafers are among the suitable techniques to be further exploited.

6. ACKNOWLEDGMENTS

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EXTENDED SOURCES IN THE XMM-NEWTON SLEW SURVEY

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ABSTRACT

The low background, good spatial resolution and great sensitivity of the EPIC-pn camera on XMM-Newton give useful limits for the detection of extended sources even during the short exposures made during slewing maneouvers. In this paper we attempt to illustrate the potential of the XMM-Newton slew survey as a tool for analysing flux-limited samples of clusters of galaxies and other sources of spatially extended X-ray emission.

Key words: X-rays; XMM-Newton, slew, survey.

1. INTRODUCTION

The XMM-Newton slew survey project has currently catalogued of the order of 4000 sources from 15% of the sky, with a limiting flux of ~ 10^{-12} ergs s⁻¹ cm⁻² in the 0.2– 12 keV energy band (Freyberg et al., 2005). Up to 20% of these sources are reported to be extended by the source detection software. While much work remains to be done on removing spurious sources, many identifications can already be made with known clusters of galaxies, groups of galaxies, nearby galaxies or supernova remnants.

At the flux levels probed here a significant fraction of sources are expected to be extended. In the Einstein slew survey (Elvis et al., 1992), which covered $\sim 50\%$ of the sky, 143 extended sources (clusters, galaxies and SNR) were found representing 17% of the detections. In the deeper ROSAT bright source catalogue (Voges et al., 1999) $\sim 6\%$ of the uniquely identified sources were found to be galaxy clusters.

2. PROCESSING

A description of the general processing steps for slew data together with the solution of the particular attitude reconstruction issues has been presented elsewhere (Read et al., 2005; Saxton et al., 2005). The source detection pipeline, consisting of a chain of the *EMASK*, *EBOXDE*-*TECT*, *ESPLINEMAP* and *EMLDETECT* tasks, has been tuned to detect point sources in the very low background conditions usually associated with slew exposures. An assessment has been made on slew images containing known extended sources, to find the best parameters to use within this pipeline to detect extended features. This showed that the parameters currently used are also optimal for detecting extended sources up to a diameter of a few arcminutes, with the caveat that a 'Beta' model gives a better fit to the spatial profile of clusters of galaxies than the default 'Gaussian' model.

3. RESULTS

In Figure 1 the high significance (DET_ML > 10) extended sources are shown with the extension parameter plotted against the number of detected background subtracted counts. Sources associated with known Abell and Zwicky catalogue clusters are circled and many detections remain to be identified.

3.1. Clusters of Galaxies

The slew survey covers a large sky area to a depth which is comparable with some of the better previous all-sky Xray cluster surveys (Fig. 2). In the regions of overlapping slews, such as the ecliptic poles, co-adding data will lead to a deeper survey albeit over a smaller area.

Cross-correlations with the Abell and Zwicky catalogues show 55 coincidences of slew sources with known clusters. Of these, 37 are detected as extended objects. The very brightest examples contain more than 100 counts, sufficient to show some cluster morphology (Fig. 3).



Figure 1. A plot of background subtracted counts against the extension parameter, measured in units of 4.1 arcsecond pixels and limited to 20 pixels. Points coincident with known clusters are circled, although some clusters apparently detected with zero extension, may in fact be coincidences with unrelated point sources. The branch showing increasing extension for very bright sources is due to pile-up effects distorting the radial profile.

3.2. Supernova Remnants

A number of famous supernova remnants have been detected so far in the slew, including, Vela, Puppis-A, N132D and W44. The nature of the slew means that large areas of the remnants are imaged (Fig. 4) and detailed two-colour maps of the big remnants will be built up as the slew density increases.

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Figure 2. A plot of cluster survey depths v area. The XMM slew curve will move to the right as more slews are accumulated. Other surveys are based on ROSAT data with the exception of the EMSS and XMM-LSS (see Pierre et al. (2005)).



Figure 3. X-ray contours of a smoothed slew image of Abell 2029 overlaid on a digital sky survey image.



Figure 4. X-ray contours of the Vela supernova remnant overlaid on a DSS image.

THE PLANK MISSION AND X-RAY SOURCES

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ABSTRACT

The Planck Cosmic Microwave Background mission, which is planned to be launched in 2007 will map th entire sky at frequencies 30-860 GHz, with a sensitivity depending on direction and frequency. Some X-ray sources as AGNs and X-ray binary systems may be detected as foreground galactic and extragalactic point sources. Due to many detectors in the focal plane and the scanning strategy, light curves for a few variable sources can be constructed for periods up to 20 days. The possibility to make co-ordinate microwave and X-ray observations may be of interest for the X-ray community.

Key words: ESA; Planck mission, X-ray sources.

1. INTRODUCTION

The ESA Planck mission (Villa, Mandolesi & Butler 2003) main purpose is to investigate the Cosmic Microwave Background (CMB) radiation. The launch date is at the moment set to Aug. 15, 2007, and it will be launched together with the Herschel (IR) 3.5 m space telescope. The Planck observatory will carry a 1.5 m telescope which will focus radiation from the sky unto two arrays of detectors: one set of 22 extremely sensitive low frequency radiometers (LFI), covering frequencies from 30 to 70 GHz, and one set of 48 bolometers (HFI) covering frequencies from 100 to 860 GHz. The entire sky will be mapped twice. To get a clear view of the CMB radiation, foreground sources have to be identified and removed.Many thousands galactic and extragalactic sources will be detected this way. Some of these will also be X-ray sources.

1.1. Scan pattern and detection of variability

The Planck observatory will move in a Lissajou orbit around L2. The orbital velocity will be about 2.5 archmin per hour, and the satellite spin rate will be about one revolution per minute. However, due to the distribution of

detectors in the focal plane, a point source will be "seen" by the various detectors at different times, and observed many times. The actual numbers of observations will depend on the final scan pattern and the ecliptic latitude of the source. For instance a point source at 70° ecliptic latitude will be observable for about 20 days, and detected in 30 scans within the FWHM of the 30 GHz detectors main beams (Terenzi et al 2002). In other words, we may get a light curve with 30 points spread over 20 days at this frequency if the source each time is detected. At lower ecliptic latitude the coverage will be shorter - down to 7 days near the ecliptic plane. Simulations show that the precision in the flux reconstruction depends on the average flux of the source, the ecliptic latitude and the frequency. (Terenzi et a.l 2002). Due to the many frequencies covered, the spectral index and spectral index variations will also be determined.

A Quick Detection System (QDS) will be used as a tool for detection of variable point sources which may be of interest for rapid follow up at other wavelengths. QDS is designed primarly as a tool for detection of outburst of active galaxies, but may also detect outburst of a few interacting binary systems - many of those being X-ray transients. Since data will be transmitted from the Planck observatory to the ground station only once per day, and the first processing takes some time, it means that "quick" in this context is a few days.

The scan pattern will be repeated after one half year, so it will also be possible to detect variability on that time scale. An Early Release Compact Source Catalogue is planned to be released 22 months after launch of the Planck observatory.

1.2. The full mission sensitivity

After the mission is completed a the final point source catalogue will be prepared. The plan is to published it 42 months after launch. Table 1 gives the expected full mission point sources detection limits (3σ) and the beam width for the different detectors.

Table 1. Estimated full mission detection limits (3σ) for point sources

Frequency	Wavelength	Detection	Beam
requercy	wavelength	Dettetion	Dean
		lımıt	size
[Ghz]	[mm]	[mJy]	[arcmin]
30	10	39	30
44	6.8	57	23
70	4.2	75	14
100	3.0	27	9.2
143	2.1	33	7.1
217	1.4	33	5.0
353	0.85	57	5.0
545	0.55	114	5.0
857	0.35	129	5.0

2. EXTRAGALACTIC POINT SOURCES

The Planck observatory will make the first all sky survey at mm and sub-mm wavelengths that is sensitive enough to detect thousands of extragalactic sources. The LFI instrument will see mosty very extreme sources like blazars and very young and compact radio sources as the Gigaherz Peaked Spectrum (GPS) sources, or Compact Symmetric Objects (CSO). The fact that it will provide us with a full-sky, unbiased survey will tell us whether we have missed significant numbers of such extreme sources because they appear insignificant in the long wavelength surveys. We may also expect to obseve radio afterglows of some gamma ray bursts.

The HFI instrument will see the brightest and the coolest IRAS type galaxies. Most of them should be already be cataloged objects but again the survey will be unbiased, and may find some very low temperature objects. The large population of dusty galaxies span a wide range from low redshift star forming galaxies to active sources (starburst and AGNs) at high redshift.

Finally, and perhaps most crucially, Planck will find thousands of clusters of galaies by their Sunyaev-Zel'dovich (SZ) signal, a direct measure of the electron pressure in the cluster. These should both supplement X-ray selected clusters and provide many interesting targets for future Xray observations. The important point is that the Planck SZ survey will be unbiased, and have very different selection criteria than X-ray surveys.

3. GALACTIC POINT SOURCES

The galactic point sources detected by Planck may either be related to star birth or to the late stages of stellar evolution. Related to star birh we will find HII rgions an star foming complexes – more than 1400 sources with eiher a cold dust (50K) or hot (10 000K) free-free radiation are expected to be detected at the Planck frequencies. In addition we nay find a large number of cold (15K) cores of molecular clouds.

Among the late stellar stages we may observe post-AGB stars with expanding dusty shells, and planetary nebulae with dusty envelopes. The many frequencies may make it possible to detect multiple cold dust shells related to previous episodes of mass ejection.

3.1. Interacting binaries and transient X-ray souces

We expect only a few interacting binary systems to be detected by the Planck instruments. The prime candidates are X-ray binaries, of which 20% show radio syncrotron emission. Most of these objects have episodic obutburst, and more than 25 may be above the detection limit at some time during the Planck mission. Only a few objects are in a persistant high state and of these only SS 433 and GRS 1915+105 are bright enough to be detected. We also expect to detect some symbiotic stars, in particular those with dust shells (D-type), which will show up at the higher frequencies.

4. CONCLUSION

The Planck all sky suvey is an unique possibility to obtain an unbiased survey of galactic and extragalactic microwave point souces. The QDS gives the opportunity to organise follow up observations at other wavelengths of variable sources shortly after the Planck detection. Knowing the scan pattern on beforehand makes it possible to do simultaneous observatons at other frequencies of known objects that Planck may detect, included many X-ray sources which also have radio and microwave components in their spectra. Approximate scan pattern will be known at the start of each of the two full sky surveys, and the final scan pattern will be known two weeks before it is executed. This should give opportunities to prepare simultaneous observations at other frequencies.

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THE DEVELOPMENT OF A BACK-ILLUMINATED SUPPORTLESS CCD FOR SXI ONBOARD NEXT

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ABSTRACT

We give overview and the current status of the development of the Soft X-ray Imager (SXI) onboard the NeXT satellite. SXI is a back-illuminated supportless CCD (a combination of "back-illuminated CCD" and "supportless CCD") whose imaging area and the supportless region are 42×42 mm² and 30mm ϕ , respectively. The goal of the thickness of the depletion layer is 300μ m, which enables us to cover the energy range of 0.3 - 25 keV. The evaluation model 'CCD-NeXT1' with the size of 24×48 mm² shows no performance change due to the thinning process. The test model of P-channel CCD was confirmed to have high quantum efficiency above 10 keV with an equivalent depletion layer of 300m.

Key words: LATEX; the NeXT satellite; X-ray CCD.

1. SXI ONBOARD THE NEXT SATELLITE

The 5th Japanese X-ray astronomical satellite, NeXT (New X-ray Telescope), is proposed to be launched around 2012 in order to investigate the non-thermal universe, such as hard X-ray components in galaxy clusters and SNRs, hidden AGNs and their contribution to the cosmic X-ray background (1). The NeXT satellite will be equipped with three sets of hard X-ray telescopes with multilayer supermirrors (Hard X-ray Telescope: HXT) focusing hard X-rays up to $60 \sim 80$ keV (2), and a wideband camera (Wideband X-ray Imager: WXI) as the focal plane detector of HXT.

An X-ray CCD is one of the most popular focal plane detectors for the modern X-ray satellites like Chandra, XMM-newton and Suzaku, because of its well balanced good performances on the spectroscopy, imaging and



Figure 1. The schematic view of the WXI.

time resolution (3; 4; 5). However, achieving a quantum efficiency of 10% for X-ray with an energy of 40 keV requires a depletion layer of $\sim 1000 \mu m$, which is almost impossible. High Z material is essential to detect such hard X-rays. On the other hand, the performances below 10 keV of the high Z solid detectors such as CdTe are poorer than those of X-ray CCD. Thus, no single detector can cover the entire 0.3-80 keV band with the best performances. Thus, we have been developing a hybrid camera WXI, by combining the X-ray CCD and a CdTe pixel detector (6; 7; 8; 9). As shown in Figure 1, WXI consists of two sub-instruments; the soft X-ray imager (SXI) and the hard X-ray imager (HXI). SXI is a CCD camera with a thick depletion layer for the lower energy band below 10-20 keV. HXI is based on CdTe pixel detector covering the hard X-rays above 10-20 keV (10).

SXI is required to detect soft X-rays efficiently and pass hard X-rays through the CCD toward the CdTe pixel detector of HXI without excessive loss of photons. Since energy and position resolution of the CCD is superior



Figure 2. The upper and lower pictures show the CCD side and the back side of CCD-NeXT1, respectively.

to those of CdTe, it is desirable for the CCD to have as high a quantum efficiency for hard X-rays as possible. From the discussion stated above, the supporting package below the imaging area of the CCD in SXI is removed in order to pass the hard X-rays toward HXI without loss (a supportless CCD). Additionally, we adopt a back-illuminated CCD by removing the field free region in order to improve the quantum efficiency at the lower X-ray energy (a back-illuminated CCD). The removal of the field free region from the CCD also improves the quantum efficiency around the X-ray energy of 10 keV. Thus, in SXI, we develop a new type of CCD, 'a back-illuminated supportless CCD', in which the both of the back supporting package and the field free region are removed.

2. CURRENT STATUS OF THE DEVELOPMENT

N-channel CCD and CCD-NeXT1 In order to confirm the principle of the supportless CCD, we processed and evaluated a small test model with the size of $12 \times 12 \text{mm}^2$, a depletion layer of $\sim 70\mu\text{m}$ and the total thickness of $\sim 150\mu\text{m}$. We found no performance degradation due to the thinning process (11). Next, we have constructed an evaluation model 'CCD-NeXT1', whose pixel size and format are $12 \times 12\mu\text{m}$ and 2000×4000 , respectively (Figure2). CCD-NeXT1 is confirmed to have the depletion layer of $77\mu\text{m}$, the read out noise of 5e (RMS) and the energy resolution of 140eV for 6 keV X-rays. After the successful development of the small test model, We have been examining "CCD-NeXT2" with the imaging area of $49 \times 49 \text{mm}^2$, which matches the required size for SXI.

P-channel CCD In order to achieve high quantum efficiency for hard X-rays, we have been developing Pchannel CCD, which is a new type of CCD collecting holes instead of electrons, from early 2002 together with National Astronomical Observatory of Japan (12). As given in Figure 3, high quantum efficiency equivalent with the depletion layer of $\sim 300\mu$ m has been already achieved (11). We also have processed the fully depleted back illuminated type of the CCD with the thickness of 200μ m, successfully. We have started processing an eval-



Figure 3. The quantum efficiency of P-channel CCD Pch8A-7-4 compared with the one of XIS (FI-CCD) onboard Suzaku

uation model "CCD-NeXT3" whose pixel size and format are $15 \times 15 \mu m^2$ and 2000×4000 , respectively.

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