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 $0.2 - 12$ keV band with exposures of less than 15 s and a sky coverage of about 6300 square 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.
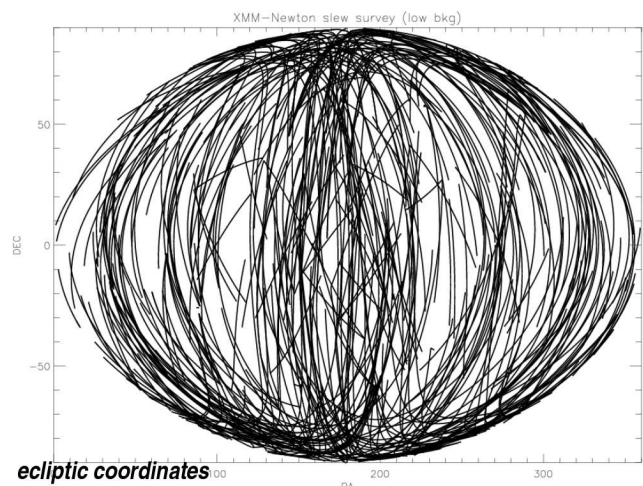

Figure 1. Sky distribution of 465 EPIC-pn slews (FF, eFF, LW modes) in ecliptic coordinates. Note that slews are performed close to great circles due to solar angle constraints.

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_{ft}, any image of an X-ray source scanned during a slew is distorted along slew direction by $\rho \times t_{ft}$.

Table 1 lists the frame times for all EPIC imaging modes where all CCDs (7 for EPIC-MOS and 12 for EPIC-pn) 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
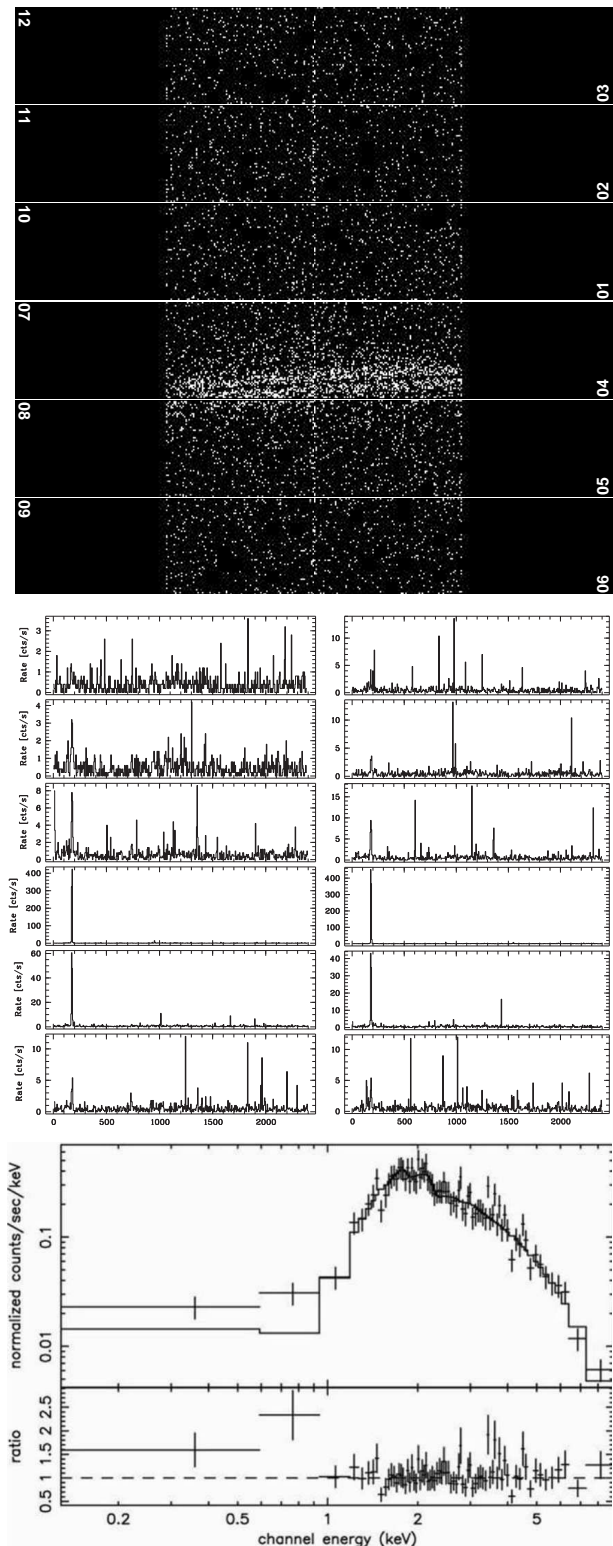

Figure 2. Example of a bright source found in "pilot-0" study. Top: detector image, LW mode. Middle: light curves of each CCD in same orientation as above (5 s time bins, $0.2-12\,keV$); the source can clearly be identified as strong increase in CCDs 7 and 4. Bottom: source spectrum.
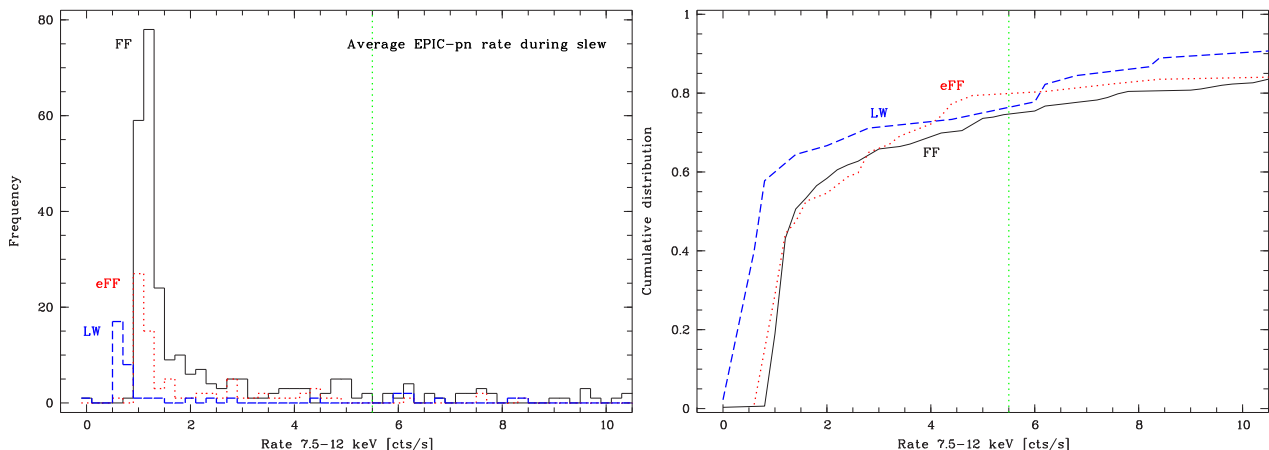
Figure 3. Distribution of EPIC-pn count rates in the $7.5 - 12\,keV$ band, for the total FOV averaged over a complete slew. Left: differential distribution for FF *(solid),* eFF *(dotted), and* LW *(dashed) modes. Right: the corresponding cumulative distributions. The vertical line indicates the threshold of 5.5 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_{ft}, and distortion of the point spread function assuming a slew rate of $\rho = 90\,arcsec\,s^{-1}$. For details see text.

Mode	Frame time [s]	Slew distortion [arcsec]
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` set-up. 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
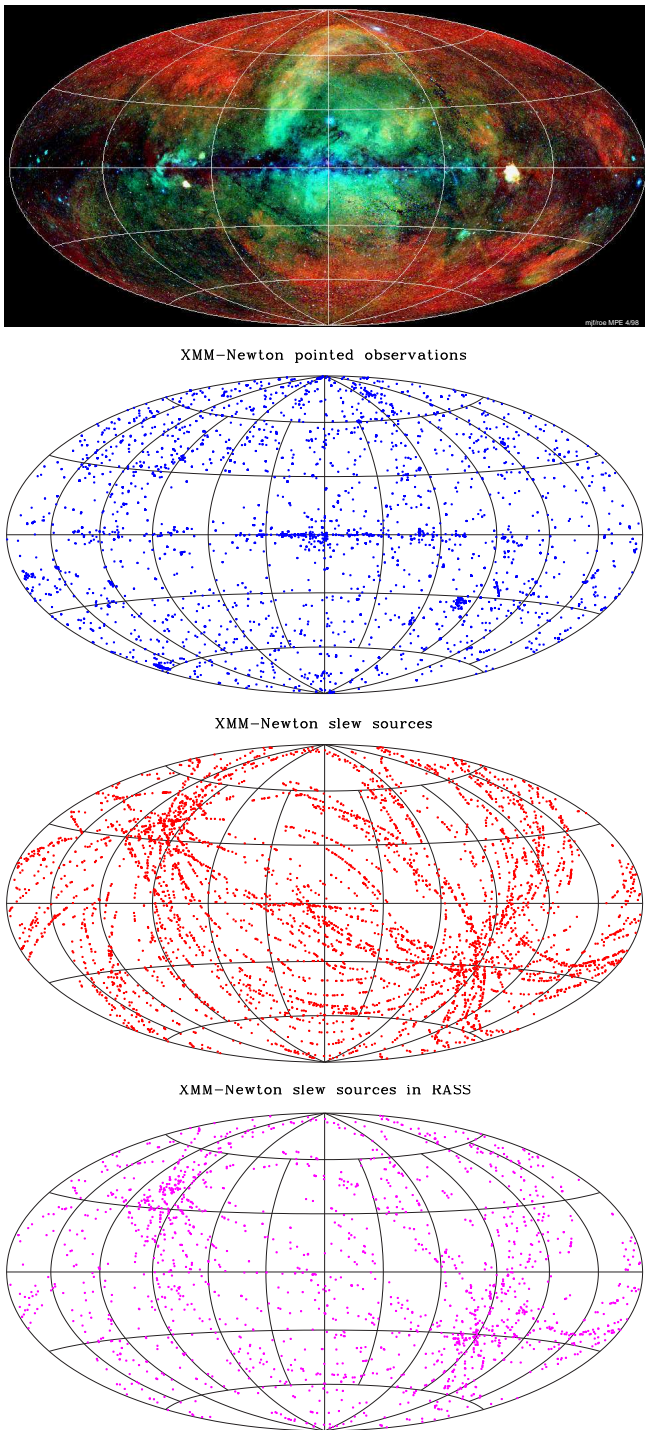
Figure 5. *Comparison of RASS* $(0.1 - 2.4\,keV)$ *and XMM-Newton* $(0.2 - 2.0\,keV)$ *count rates for slew sources with RASS counterpart*

distribution of these rates for the highest band chosen $(7.5 - 12\,\mathrm{keV})$ 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 "low-background 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 $> 35\,\mathrm{s}$ (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).

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.*
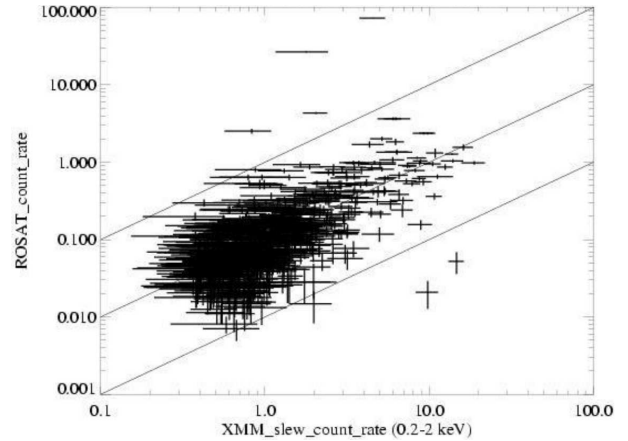
3.4. Current scheme

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 $100\,\mathrm{eV}$ (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 $7.5 - 12\,\mathrm{keV}$ band exceeding $5.5\,\mathrm{counts\,s^{-1}}$

- construct images and exposure maps in 3 bands: soft ("RASS") band $0.2 - 2.0\,\mathrm{keV}$, hard ("beyond RASS") band $2 - 12\,\mathrm{keV}$, total band $0.2 - 12\,\mathrm{keV}$. Note, that in the range $0.2-0.5\,\mathrm{keV}$ only single pixel events are used (`PATTERN==0`) and above $0.5\,\mathrm{keV}$ also double pixel events (`PATTERN.le.4`), and discard subimages with exposures $> 35\,\mathrm{s}$.

4. THE CATALOGUE: XMMSL1

The XMM-*Newton* Slew Survey catalogue XMMSL1 will consist of the order of 4000 sources detected in the total band ($0.2-12\,\mathrm{keV}$), 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.
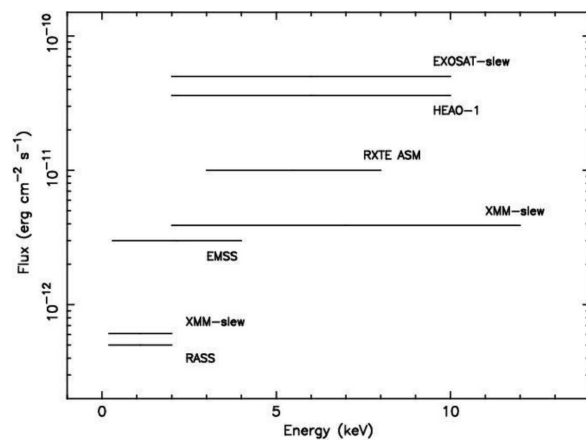

Figure 6. Sensitivity limits for various X-ray surveys.

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 $6(4.5)10^{-13}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$ (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 ($4(3)10^{-12}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$) than the RXTE survey (Revnivtsev et al., 2004) – which has a positional accuracy of only $\sim 1°$ – 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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