In-orbit performance of the SAX low energy concentrator system (LECS)

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ABSTRACT

The Low Energy Concentrator System (LECS) is an imaging X-ray spectrometer. It is one of the narrow field instruments onboard the SAX satellite and covers the energy range from 0.1 to 10 keV. The good low energy response of the detector is achieved by using a driftless gas cell and a thin multilayer polyimide foil as an entrance window.

SAX was launched on April 30th 1996. Following a two months commissioning phase, the satellite has entered the science verification phase. We report here on the first in-flight data acquired with the LECS. Using back-ground measurements and well known X-ray sources, we present the first results of the in-orbit performance and calibrations and compare them to ground measurements acquired at synchrotron and long beam X-ray sources.

After a brief description of the instrument we discuss some aspects related to the ground calibrations. In particular the entrance window characteristics and the particularities of a driftless detector design are reviewed. By correcting for the X-ray absorption depth, we also show how the energy resolution could be enhanced.

Keywords: low energy, X-ray, imaging, GSPC, detector, astronomy, Cyg X-1, NGC-4151

1 INTRODUCTION

SAX is an Italian/Dutch spacecraft which has been placed into low-Earth orbit by an Atlas I launch vehicle on April 30th 1996. The orbit is circular at a height of 600 km with an inclination of 4° to the equator. This orbit takes maximum advantage of the shielding of the Earth's magnetic field. During the expected lifetime of up to 4 years, SAX will make 1000–2000 observations of cosmic X-ray sources over the unprecedentedly wide energy range of 0.1 – 300 keV. Descriptions of the mission are to be found in Spada,¹ Butler & Scarsi,² Scarsi³ and Boella et al.^{4,5} The scientific objectives of the mission include broad band spectroscopy in the energy range 0.1–10 keV with imaging resolution of 1', non-imaging spectroscopy in the energy range 3–300 keV and variability studies of X-ray source intensities and spectra on timescales from milliseconds to months, see Perola.⁶ Mission operations are conducted from Rome, Italy and are designed to allow a flexible response to any targets of opportunity.

The payload consists of the Phoswich Detector System (PDS), the High Pressure Gas Scintillation Proportional counter (HPGSPC), two Wide Field Cameras (WFC), three imaging Medium Energy Concentrator Systems (MECS) and the imaging Low Energy Concentrator System (LECS). Descriptions of these instruments can be found in Martin,⁷ Piro,⁸ Chiappetti,⁹ Giarrusso,¹⁰ Frontera,¹¹ Jager¹² and Mels.¹³ All the instruments are coaligned except for the WFCs which point in opposite directions along an axis perpendicular to the other instruments. Each imaging GSPC is located at the focal plane of an X-ray concentrator system. In order to extend the sensitive range of the imaging spectrometers to <1.3 keV, the LECS dispenses with the separate drift and scintillation regions of conventional GSPCs and utilizes an extremely thin entrance window. This instrument was provided by Space Science Division (SSD) of the European Space Agency and is described here. Its primary

objective is to provide better energy resolution at low energies than currently available non-dispersive detectors and so to open up new areas of astrophysical interest.

The last few years have been an exciting time for X-ray astronomy with the launches of the ROSAT, ASCA and XTE satellites. ROSAT provides high sensitivity and spatial resolution in the 0.1–2.5 keV energy range, but with only moderate spectral resolution, see Trümper.¹⁴ XTE concentrates on timing studies in the 2–200 keV energy range with moderate spectral resolution, see Swank.¹⁵ The ASCA payload consists of both imaging CCD and GSPC detectors, Tanaka.¹⁶ The CCD detectors provide an energy resolution, ΔE , of 100–150 eV over the ~ 0.5 –10 keV energy range, while the GSPCs provide $\Delta E \sim 500$ eV at 6 keV over the energy range 1.0–10 keV. The good spectral and spatial resolutions, robustness and low power requirements of CCD detectors have ensured that they have become the preferred detectors for future X-ray spectroscopic investigations (Weisskopf,¹⁷ Bignami¹⁸ and Wells¹⁹). While their development is still proceeding, it is worth comparing their properties with those of GSPCs:

- The resolution of a typical GSPC detector at 6 keV of 500 eV is a factor ~ 4 worse than a CCD. However, the resolution scales approximately as $E^{1/2}$ and so becomes comparable to that of CCDs at low ($\lesssim 0.5$ keV) energies.
- GSPC detectors provide extremely good time resolution of up to a few μ s. This should be compared with a time of ~ 2 s needed to read out a typical CCD. CCD time resolution can be improved to tens of ms by continuously reading the device. The spatial distribution of the observed X-rays then represents timing information.
- In X-ray astronomy CCD detectors are used in photon counting mode. This means that the mean arrival rate should be < 0.1 photons pixel⁻¹ frame⁻¹ which can place severe constraints on the maximum source strength allowed. The maximum count rate of the LECS is limited by the electronics to be < 2000 counts s⁻¹.
- The energy resolution of GSPCs is known to be extremely stable, whereas there are still concerns as to the effects of large radiation doses on CCDs (e.g. Holland²⁰).
- GSPCs have good background rejection capabilities using a variety of techniques over and above those used by CCDs.

2 LECS DESCRIPTION

The LECS consists of Mirror, Detector, Electronics and Gas Units. The Mirror Unit is provided by the Italian Space Agency (ASI). The major components of the SSD provided units are shown in Fig. 1 and the overall performance is summarized in Table 1. A complete review of the instrument can be found in Martin⁷ and Parmar.²¹

2.1 Detector and mirror units

The LECS uses one of the 4 mirror units (MU). Each MU consists of 30 nested, Au coated, confocal mirrors with a double cone approximation to Wolter I geometry, see Citterio.²² The geometric area is 124 cm² and the nominal focal length is 185 cm. The calibration and performance of the flight MUs is described by Conti.²³

In order to deflect any plasma that might pass through the MU, a plasma protection grid is mounted on the underside of the unit. This consists of a fine pitched Au-coated W grid, placed at +28 V potential.

The Detector Unit (DU) consists of a gas cell, a photo-multiplier tube (PMT), Front End Electronics (FEE) and two high-voltage supplies. The detector is protected by an Al cover on which a shutter mechanism is mounted. Additional plasma protection is ensured by an ultra-thin window located just beneath the shutter. The protection window consists of two layers of Polyimide with a total thickness of 200 nm, separated by a layer of AlN and coated with a layer of AlN and C on the external surfaces. Mechanical strength is provided by a 250 μ m hexagonal Polyimide grid. The top cover has a thin Be disk mounted on its interior upper surface in order to minimize any X-ray background induced by electron emission from the gas cell top disk which is at a potential of -20 kV.

Figure 1: LECS instrument schematic

Parameter	Value	Parameter	Value
Energy Range	0.1–10.0 keV	Entrance window size	20 mm diameter
Energy Resolution at 0.28 keV	32% FWHM	Image scale	1'86 mm ⁻¹
Energy Resolution at 6 keV	8.8% FWHM	Time Resolution	16μs
Angular Resolution at 0.28 keV	9'7 FWHM	Maximum Throughput	2000 events s ⁻¹
Angular Resolution at 6 keV	2'1 FWHM	Energy Spectrum	1024 channels
Effective Area at 0.28 keV	22 cm ²	Image size	256 by 256 pixels
Effective Area at 6 keV	50 cm ²	Pixel size	14'' by 14''
Field of view	37' diameter circular		

Table 1: LECS overall performance summary

The detector also contains two ⁵⁵Fe radioactive sources which constantly illuminate regions of the detector outside the field of view (FOV), allowing the position and energy gains of the instrument to be continuously monitored.

The method of operation of the detector is similar to that of a conventional GSPC (see Inoue,²⁴ Davelaar,²⁵ Peacock²⁶ and Simons²⁷). An X-ray which is absorbed in the cell gas liberates a cloud of electrons. A uniform electric field between the entrance window kept at -20 kV and a grounded grid, causes scintillation of the Xe gas as the electrons travel towards the grid. The UV light from these scintillations is detected by the PMT mounted at the rear of the cell. The amount of light produced is proportional to the energy of the incident X-ray but, unlike a conventional GSPC, also depends on the depth at which the X-ray photon was absorbed. This depth is determined by measuring the duration of the scintillation light and is referred to as the "Burstlength". Thus an X-ray absorbed deep within the gas cell will have a shorter burstlength than one absorbed directly below the entrance window. The negative potential on the window and the high electric field ensure that electrons created by X-rays absorbed just beneath the entrance window have a high probability of entering the scintillation process.

In order to let low energy X-rays penetrate the cell, an extremely thin multi-layer entrance window consisting of three layers of Polyimide separated by Al/AlN multilayers has been developed. This construction was chosen to minimize the leak rate and sensitivity to atomic oxygen corrosion. The Al and AlN layers act as gas permeation barriers while the Polyimide provides mechanical support. The strength to support a differential pressure of over

1 bar is provided by a fine grid and a strongback. The strongback is made of 50 μm thick W bars with a height of 3 mm and a pitch of 2.2 mm. The fine grid consists of 25 μm thick W foil which subdivides each strongback square into a matrix of 8 by 8 squares.

The PMT is a ruggedized Hamamatsu R5218 tube with a 2.8 mm thick quartz entrance window of 76 mm diameter contained in a mu-metal housing to shield it from external magnetic fields. Nine anodes, each $13 \times 13 \text{ mm}^2$ are positioned in a 3×3 square configuration with a separation of 1 mm. The anodes are separately read out and operated as an Anger camera²⁸ to provide spatial information.

Within the FEE, each of the signals from the nine PMT anodes are fed to separate charge-sensitive amplifiers with a 60 μs time constant. The amplified signals are then combined to provide the energy (S_a), X (S_x) and Y (S_y) positions and veto (S_v) signals. The veto signal, S_v , provides a measure of the light distribution in the detector. This signal has a high value for events that occur close to the center of the FOV and a low one for events that occur outside the FOV. The veto signal can also be used to distinguish between particle events (which typically appear extended and therefore have low veto values) and on-axis X-ray events. The four signals are buffered and passed to the Electronics Unit (EU) for further processing.

2.2 Electronics unit

The EU provides the electrical interface between the instrument and the spacecraft. It processes the analog signals from the FEE and derives also the pulse lengths, "BL". Upon qualification, the energy channel, S_a , is converted to a 10 bit value (PHA signal) and the other channels are converted to 8 bit values and are referred to as the RAWX, RAWY, VETO, and BL signals (coming from the S_x , S_y , S_v signals and the burstlength determination circuitry, respectively). An on-board counter, synchronized to the spacecraft's ultra-stable clock, time-tags the events with 16 μs resolution. Between the time the EU detects an event and its conversion, the acquisition chain is inhibited to prevent subsequent pulses from affecting the current measurement. The time the instrument is inhibited in this way is accumulated in a deadtime counter. Whenever a non-qualified event is detected, the analog-to-digital conversion process is aborted in order to minimize the deadtime. The deadtime for each event is amplitude dependent, and is in the range 64 μs , for non-qualified events, to 250 μs for full-scale events.

The system runs under the control of a real-time operating system, which schedules the tasks for instrument monitoring and protection, command processing and execution and data processing. The digitized values are finally packetized and transmitted to the spacecraft's main computer which forwards the data to ground.

2.3 Gas unit

The original specification on the leak rate of gas cell entrance window was sufficiently high to require a gas filling system. However, the leak rate of the final design is so low ($<10^{-6} \text{ mbar liter s}^{-1}$) that such a system is no longer required for this purpose. Instead, the GU can be used to completely vent and refill the gas cell should the gas become contaminated. The unit consists of two identical 0.5 liter Ti reservoirs containing 20 bar liters of Xe, input and vent valves, a pressure transducer, a thermistor and the necessary structure and piping.

3 INSTRUMENT PERFORMANCE AND CALIBRATION

Great care has been taken to ensure a good calibration of the LECS. Each of the critical components has been separately calibrated and then the entire calibration has been verified at instrument level. The measurements have been performed using SSD's 6 meter X-ray beam, the Berlin synchrotron facility (BESSY), and the PANTER long-beam X-ray facility of the Max Planck Institut für Extraterrestrische Physik near Munich. All measurements reported here were performed in vacuum with the nominal voltages of -20 kV on the cell and 1082 V on the PMT, which are also the nominal settings in flight. The two calibration sources which are located outside of the field of view are constantly monitored and provide a means to compensate for gain variations due to temperature. Gain is defined here as the ratio of the energy of an event and the mean PHA channel at which it is detected.

After gain correction using the cal sources, the energy channels are referred to as Pulse Invariant (PI) channels. Since the GSPC gain is very sensitive to gas impurities, the calibration sources could also be used to correct for this effect. However, extensive laboratory measurements over the last year on the flight spare model have shown that the detector gain is extremely stable. Also during the 3 first months in orbit, the flight instrument has not shown any signs of gas contamination.

The particular design of this detector, dispensing with a separate drift region and using a multilayer composite entrance window required a special calibration campaign. In order to understand the results which will be shown in sections 4 and 5, we will only report here on the efforts put into the window calibration and some of the physics of the detector itself. For more details we refer to earlier papers.^{7,21}

3.1 Entrance window

The entrance and plasma protection windows' transmissions were measured using the PTB SX-700 plane grating monochromator beamline at BESSY, in the energy range 0.1 to 1.8 keV. Transmissions at 500 energy values were measured at five positions in the central window area. Energy steps as small as 0.2 eV were used around the absorption edges of the constituents. These measurements were complemented by a series of measurements in the center of each of the 8 by 8 fine grid positions in the central 3 by 3 strongback squares. Between 18 and 30 energies were used for these scans. The X-ray transmission is modeled using the mass absorption coefficients of each of the window's constituents derived from tables in Henke²⁹ and fitting the area densities. A correction function was also used to take into account the X-ray absorption fine structures (XAFS, see Bearden³⁰ and Owens³¹) near the absorption edges. Table 2 summarizes the theoretical composition, based on the design of the window, and a typical area density fit. Figure 2 shows the measured transmission of the entrance window and compares it with a 10 μm thick Be window as used on the ASCA GSPC (Tanaka¹⁶). The fitted curve matches the data well, but is not superposed for clarity. The complex structure near the edges is clearly visible.

Figure 2: Transmission of the multilayer entrance window. Also shown is the transmission of a 10 μm Be window for comparison. Arrows at the bottom mark astrophysically important emission lines.

Element	Predicted Area Density ($\mu\text{g}/\text{cm}^2$)	Predicted Thickness (μm)	Fitted Area Density ($\mu\text{g}/\text{cm}^2$)
H	4.8		4.9
C	126		130
N (total)	17.3		17
O	31		38
Al (total)	19.4	0.044	13
AlN	11.4	0.035	
PI	175	1.25	

Table 2: Predicted and nominal fitted compositions of the entrance window.

3.2 Detector physics

Figure 3 shows a representative image obtained with Fe K_α illumination to illustrate the overall performance of the LECS. The two ^{55}Fe calibration sources are visible in the upper left and lower right corners. The off-axis pin-hole images are asymmetric and extended towards the outside of the FOV. This is caused by the penetration of $\gtrsim 1.5$ keV X-rays into the cell gas before absorption. Because of the driftless design, these penetrating X-rays will give rise to lower PHA and BL values than those absorbed directly beneath the entrance window. In addition,

the variation in viewing angle and footprint of the scintillation light will cause the measured position to be shifted. The dependence of mean penetration depth on energy under the LECS nominal operating conditions is shown in Fig. 4. The effect of penetration on the LECS event data is further illustrated in Fig. 5 and 6. This shows

Figure 3: Multi pin-hole array image, Fe exposure. The calibration sources are the bright spots in the upper left and lower right corners. The circles delimit the areas used for gain mapping.

Figure 4: Mean absorption depth in Xe as a function of X-ray energy using Henke.²⁹ The positions of the Xe absorption edges and the energies of the lines used in the LECS PANTER calibration are indicated

Figure 5: Burstlength-Energy diagram for 4.77keV incident photons, i.e. just below the Xe L-III edge.

Figure 6: Burstlength-Energy diagram for 4.79keV incident photons, i.e. just above the Xe L-III edge.

burstlength (BL) versus energy for incident X-ray energies just below and just above the Xe L_{III} edge, where there is a large discontinuity in mean X-ray absorption depth (see Fig. 4). At an energy of 4.77 keV (i.e. just below the Xe L_{III} edge) the mean penetration depth is large and the extended tail of events of Fig. 5 towards lower energy and BL values (1) is caused by penetration. The events labeled as (3) are due to multiple events occurring within the EU sampling window i.e. event pile-up. This feature is prominent due to the high count rates used for these calibration measurements, but will be negligible for most astronomical sources. In contrast, Fig. 6 is an exposure at 4.79 keV, i.e. just above the edge. As expected, the effects of penetration are greatly reduced with only a small tail towards lower energies and BL values evident (1). In addition the fraction of escape photons (2) has increased due to the incident photons having sufficient energy to liberate electrons from the Xe L_{III} shell. A further discussion of these effects can be found in Simons³² and Bavdaz.³³

In order to correct for the penetration effect, we used PANTER data where the incident energies are larger

than 2.9 keV. For a given incident energy we then determined the mean PHA channel for events absorbed just beneath the entrance window (i.e. those with the largest BLs). For all other, lower, BL values, a correction was then calculated. The resulting, corrected spectra can either be represented by a Gaussian or, at energies $\gtrsim 1.5$ keV, a Gaussian plus an exponential low-energy tail. The left two panels in Fig. 7 show observed line profiles at 0.28 keV, where the mean absorption depth is small, and 8.06 keV, where it is large (see Fig. 4). The 0.28 keV line profile is well fitted by a Gaussian function, demonstrating the good low-energy performance of the instrument since the loss of significant numbers of electrons would result in a tail towards low energies, which is not evident. The 8.06 keV line shows an exponential tail extending towards lower energies. This results from the penetration of X-rays into the gas cell prior to absorption. The right panel of Fig. 7 shows the effect of BL correction on Cu_K data. The resulting LECS energy resolution is given by:

$$\frac{\Delta E}{E} = 8.84 \left(\frac{E}{6 \text{ keV}} \right)^{-0.42} \% \quad (1)$$

During normal astronomical observations there is a further complication that the actual energy of a detected

Figure 7: The response of the LECS to monochromatic radiation at energies of 0.28 keV (left panel) and 8.06 keV (center panel). The “knee” visible in the Cu_K spectra at channel ~ 850 is from $\text{Cu } K_\beta$ radiation. The right panel shows the effect of performing the penetration correction on the Cu_K spectrum assuming an incident energy of 8.06 keV

event, E_c , is not known a priori and only the probability that an event has a certain incident energy can be estimated. In the LECS data analysis software an energy value is assigned to each event taking into account this probability. The penetration correction can only then be applied. This lack of a priori knowledge of the incident energy means that e.g. the measured FWHM energy resolution of 9.0 at $\text{Fe } K\alpha$ (6.41 keV) can only be corrected to 8.6% using this technique, rather than 8.1% if the energy of the incident X-rays is known.

4 BACKGROUND

4.1 Laboratory measurements

The VETO and BL signals can be used to minimize the residual background counting rate seen in the LECS. Figure 8 shows BL plotted against VETO for on-axis B (0.18 keV) and Cu_K (8.06 keV) events. Events falling outside the FOV are excluded. The events with VETO values of ~ 20 result from multiple calibration source events being detected during a single EU sampling window. The effects of penetration are clearly seen in the Cu_K image, where a tail towards lower BL and higher VETO values is evident. This change in VETO value is caused by the increased PMT viewing angle of penetrating events which are absorbed closer to the central anode. At 0.18 keV, because of low signal strength, the BL signal distribution is significantly broadened by the EU circuitry. In addition, at low energies there is an unexpectedly large number of events with high BL values. The magnitude of this effect appears to be inversely correlated with mean absorption depth. It is possible that these events are

Figure 8: BL plotted against VETO for Boron and Cu-K

absorbed very close to the entrance window where the electric field is non-uniform due to the undulating window surface.

Figure 9 shows the allowed range of BL plotted against PI energy channel for a 90% X-ray acceptance as a hatched area. The broadening of the BL distribution at low-energies discussed above is visible, as is the effect of change in mean absorption depth around the Xe L edge at a PI channel of ~ 400 .

The LECS background counting rate within the FOV has been estimated using a $3.6 \cdot 10^5$ s exposure taken in SSD's X-ray beam. A VETO acceptance interval of 30 to 65 combined with BL cuts of the type described above were applied to the data to give count rates of $1.6 \cdot 10^{-3} \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$ for 90% X-ray acceptance and $1.8 \cdot 10^{-3} \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$ for 99% X-ray acceptance. (Note that the cm^{-2} in the count rate units refers to the window area). Figure 10 shows the effect of these selections. The observed spectrum is shown as a dashed histogram and the spectrum remaining following selection as a solid histogram. 1σ uncertainties are indicated. The count rate scale is given by the right ordinate. The efficacy of each of the selection techniques is given by the left ordinate. The increase in counts observed in the incident spectrum around channel 600 is primarily due to event pile up from the calibration sources. As Fig. 10 illustrates, these events are efficiently removed by the VETO selection. At the lowest channels there is an increase in detected event rate which is probably due to electronic noise.

Figure 9: The allowed BL range for 90% X-ray acceptance efficiency shown as a hatched region.

Figure 10: The effect of VETO and BL selection on the laboratory background spectrum within the FOV.

4.2 In-orbit background: predictions and measurements

There are at least five major components to the background which might be observed by the LECS in orbit:

- The cosmic X-ray background. Recent ASCA measurements³⁴ confirm that for the LECS, this background becomes more significant than the other components below 2keV.
- The particle induced background, which appears energy independent.
- The UV induced background. UV photons, particularly geocoronal Lyman- α , can eject electrons from the detector top surface (at -20kV) which will then hit the underside of the C coated plasma protection window, or the Be of the cover. X-ray fluorescent photons can then be detected by the DU. The detector is shielded against UV through the Al layers in the plasma protection window.
- The plasma induced background. Plasma has a similar effect as UV. The plasma protection window and the grid behind the mirrors protect the detector from plasma ingress.
- Scattered solar radiation, dominated by Thomson scattered X-rays below 0.25 keV and by the O K- α at 0.54 keV.

Figure 11 shows the first background spectrum accumulated in space with the LECS. This 20ks observation was acquired while the satellite was pointing at Polaris. The events are selected in VETO and BL as previously explained to have 99% X-ray acceptance. The cosmic X-ray background (XRB) is clearly visible below channel 200 (about 2keV). The total background count rate is $2.9 \cdot 10^{-3} \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$. The spectrum shows a small increase in counts around channel 600, as was noticed in the laboratory. Comparing with figure 10, the XRB is clearly visible below channel ~ 300 . No Al or C lines are visible which indicates that the level of plasma or UV light reaching the entrance window is low and does not contribute significantly to the background. Remembering that Polaris is a $m_v = 2$ F8 star, the instrument appears to be sufficiently insensitive to UV light for most observations. However, it was noticed during the first observations that the PMT was very noisy when the satellite is in day-

Figure 11: In-flight Background spectrum within the field-of-view, using VETO and BL selection.

time. This is likely caused by reflected Earth shine being scattered off the spacecraft baffles and into the detector. Consequently, observations are currently restricted to spacecraft night-time only. This has the beneficial effect that no scattered solar radiation is present in the background.

5 FIRST LECS IMAGES

Since the beginning of July, the instruments are in the science verification phase, during which well known X-ray sources are observed. This data will complement the ground measurements in the calibration database. Figure 12 shows the “first light” seen by the LECS. The image was taken during a 500 seconds exposure on the black hole candidate Cygnus X-1, but the pointing was 11' off-axis in the X direction. The image includes

the complete X-Y range which explains the presence of the calibration sources in the upper left and lower right corners as well as some badly encoded source events in the upper right corner, which can easily be removed by proper selections. The average source count rate was 240 s^{-1} . Figure 13 shows the spectrum accumulated after event selection (as explained in section 4). A “best fit” is superposed as are the residuals of the fit. The fitting was done using a power-law and a blackbody spectrum as well as absorption due to material in the line of sight to the source. The reduced χ^2 is 1.76 and as can be seen from the residuals, the fit is very good except for the lowest energies. This excess in the spectrum could come from poorly modeled penetration effects from photons with energies $< 2.9 \text{ keV}$. As was explained in section 4, the penetration effect is currently only corrected for higher energies. The effect could also be explained by loss of electrons to the window. Clearly more analysis is needed in this area.

Figure 12: Cyg X-1 image, all events included.

Figure 13: Cyg X-1, Energy spectrum.

Figure 14 is a image obtained from an 8000 seconds observation on the Seyfert galaxy NGC4151. The count rate is much lower than for Cyg X-1, namely 0.4 s^{-1} which explains why the background events are more pronounced in this contour plot. The apparent distortion of the center object is actually a second X-ray source identified as BL Lac object 1E1207.9+3945 (see Warwick³⁵). The accumulated spectrum is displayed in figure 15, together with a theoretical model of a blackbody plus a power-law to which an Gaussian emission line was added. The reduced χ^2 of 1.01 indicates that the ground calibrations are of an extremely high standard. Note that the soft excess of the source is clearly visible below the Carbon edge (280 eV).

Figure 14: NGC4151 image, all events included.

Figure 15: NGC4151, Energy spectrum.

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