Design and in-orbit-performance of the Position Sensitive Proportional Counter on board the X-Ray astronomy satellite ROSAT

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Abstract

A Position Sensitive Proportional Counter (PSPC) was the prime focal plane instrument on board the X-ray astronomy satellite ROSAT, a conventional multiwire counter for X-ray imaging in the energy range from 0.1 to 2.4 keV. The detector gas was a mixture of 65% Ar, 20% Xe and 15% CH_4 at a pressure of about 1.5 bar, replenished at a flow rate of 2.5 cm^{3}min^{-1}. At 1 keV the detector had an energy resolution of 41% FWHM, a position resolution of 230 μm FWHM, and a quantum efficiency of 50%. The background rejection capability in the space environment was 99.85%. The gain degradation in orbit was 1% per month for the nominal PSPC A and 1% per year for the redundant PSPC B. Within the first four years of the mission, the PSPC was used for 80% of the observing time. Thereafter, the gas supply was nearly exhausted and the PSPC was used only for special observations. After eight years a final observation was carried out with the PSPC using extremely reduced gas flow at the border of the radiation belts with a very high particle background. During this observation the detector probably suffered a discharge and within several days an increasing area with 50% gain loss developed. We report on the detector design, the in-orbit-performance of the PSPC and some results of the ROSAT mission.

Key words: Proportional counters, Aging effects, X-ray astronomy
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1 Introduction

ROSAT is a German X-ray satellite with major contributions from the UK (UV- telescope) and the US (HRI-detector and satellite launch) [1]. The satellite was launched in 1990 and operated for more than eight years in orbit. One of the main scientific objectives of the ROSAT mission was the performance of the first X-ray all-sky survey in the energy band from 0.1 to 2.4 keV with an imaging telescope. After completion of the survey ROSAT was used in pointed mode for detailed observations of selected objects.
The main scientific payload of ROSAT was an imaging X-ray telescope with a fourfold nested Wolter type 1 mirror system with a maximum aperture of 83 cm and a focal length of 2.4 m. The focal plane instrumentation [2] carried two different types of X-ray image detectors: two identical Position Sensitive Proportional Counters (nominal PSPC A, redundant PSPC B) with a sensitive area of 8 cm diameter, and one High Resolution Imager (HRI) based on micro-channel plates with a sensitive area of 2.5 cm diameter. The performances of the PSPC and the HRI complement one another. Whereas the PSPC provides energy-resolved (δE/E = 0.41 FWHM at 1 keV) X-ray images of 25 arcsec angular resolution and a field of view of 2 deg, the HRI exploits the angular resolution of the mirror system of several arcsec, but has no energy resolution and a smaller field of view. The detectors are mounted on a carousel, which allows the positioning of the desired detector in the focus of the mirror system. Except for the HRI, the whole focal plane instrumentation was developed and built in our institute.

2 Detector design and performance

The PSPC includes two multiwire proportional counters (Fig.1). The upper one, below the entrance window and a drift region of 8 mm, is the position sensing X-ray detector. The lower one is an anti-coincidence counter to discriminate against background events. We used 10 μm tungsten wires for the anode grids with a wire spacing of 1.5 mm for the X-ray detector and 2 mm for the anti-coincidence counter. For the cathode grids, 50 μm Pt-Ir wires were used with a wire spacing of 0.5 mm. The two cathode grids of the X-ray detector were electrically subdivided into strips of 3.5 mm width for the position readout of the X-ray events by the center of gravity method. The grids were manufactured on a winding machine and glued onto glass-ceramic frames. Due to a very precise spacing of the wires (± 2μm) and the grid gaps (± 5μm), we obtained a very homogeneous gas gain (variation 3%). All grids of the flight units were checked for wire spacing and wire tension. The resonance frequencies of the wires had to be above 400 Hz to survive the rocket launch. The detector window is a 1 μm thick polypropylene foil coated with

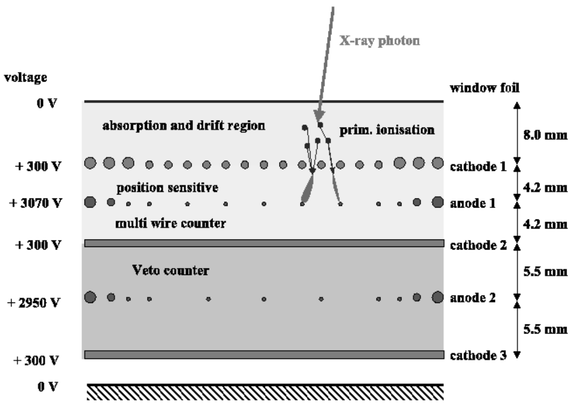

Fig. 1. Schematic diagram of the grid system of the PSPC.

carbon and Lexan. The foil is supported by wire grids and aluminium struts. The differential diffusion and the leakage of the window foil, as well as the cleaning of the detector gas from crack products required a gas flow system. The counter gas is a mixture of 65% Ar, 20% Xe and 15% CH_4 at a pressure of 1466 mbar at 22^{o}C. The detector gas was density controlled and renewed at a selectable flow rate. At nominal flow rate (2.5 cm^{3}min^{-1}) the gas volume of the detector was exchanged in about one day. A filter wheel in front of the detector window included a vacuum door with three calibration sources (Al target excited by an Fe^{55}source, 1.486 keV X-ray line) for ground checkout and in-orbit calibration (Fig.2).

Several watchdog functions were implemented in the onboard software of

Fig. 2. Integrated Detector. On top of the detector housing is a filter wheel with four positions: open, closed, Boron filter and vacuum door with three calibration sources.

the experiment computers to insure the nominal function of the PSPC: Limit checks of housekeeping values like gas pressure, high voltage and count rates were carried out continuously and in case of an 'out of limit' the detector was switched off. At its northern and southern part the ROSAT orbit (circular, 580 km, inclination 53 deg) touches the inner radiation belt and crosses the South Atlantic Anomaly, regions with extremely high particle fluxes. During passage through these regions of the orbit the detector was switched off.

The PSPC operated at a gas gain of 2×10^4. At 1 keV it had an energy resolution of $\delta E/E = 0.41$ FWHM, a position resolution of 230 μm FWHM (Fig.3) and a quantum efficiency of 50%. Energy and position resolution are proportional to $E^{-0.5}$. The background rejection efficiency for charged particles and induced fluorescent radiation was 99.85%, which is very essential for space application.

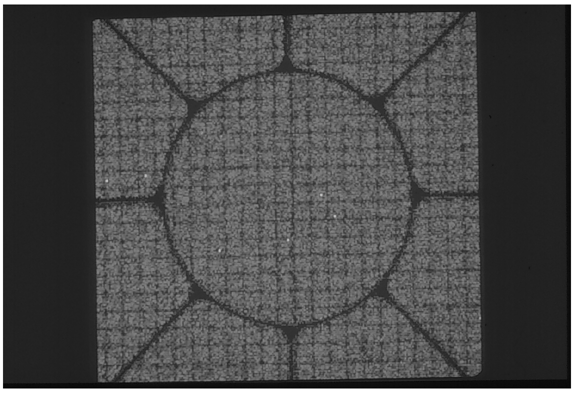

Fig. 3. Flat field illumination of the central part of the PSPC window with 0.93 keV X-rays. The shadows of the star-shaped window support structure and the 100 μm support wires demonstrate the imaging capabilities of the PSPC.

3 In-orbit-performance and aging effects

The following types of events are seen by the PSPC in the space environment. The majority of events are produced by minimum ionizing particles with a count rate between 100 cts s^{-1} and 500 cts s^{-1}. Depending on the incidence angle, they deposit an energy of 10 to 100 keV in the sensitive volume of the detector. Heavily ionizing particles with a count rate of about 2×10^{-2} cts s^{-1} can deposit up to 100 MeV in the detector. Event rates of X-rays, focused by the mirror onto the detector, depend on the source strength of the actual object viewed by the telescope. The Crab Nebula, one of the strongest celestial X-ray sources, had a count rate of about 800 cts s^{-1} in 1 mm^2 of the PSPC. Sco X-1, the strongest X-ray source in the sky, was excluded from direct observations.

The nominal PSPC A operated for eight months in orbit without any problems. During a strong solar flare, when the attitude control system of ROSAT failed, the Sun came in the field of view of the telescope. During that event the window foil of PSPC A was destroyed. From that time on the observations had to be carried out with the redundant PSPC B.

The gains of the detectors were periodically tested with the 1.5 keV X-ray line of the calibration sources, shown in Fig.4. PSPC A had a gain shift of -1% month^{-1} (Fig.4 period 1). The gain shift of the redundant PSPC B was

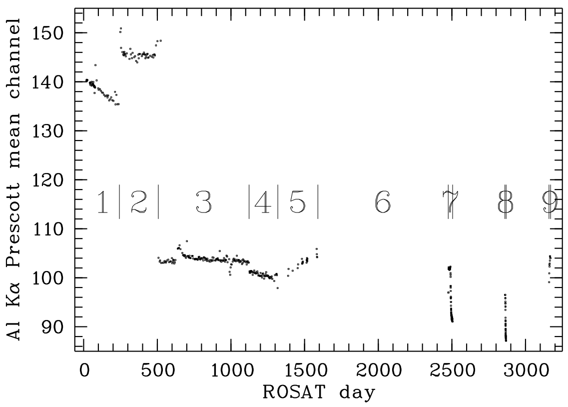

Fig. 4. The diagram shows the peak position of the Al Kα calibration line in adc channels reflecting the gas gain of the PSPCs during the lifetime of ROSAT. During time period 1, the nominal PSPC A was used and afterwards for periods 2-9 the redundant PSPC B. The larger step in gain between period 2 and period 3 is due to a change in the high voltage setting of the detector.

much less and of the order of -1% year^{-1} (Fig.4 period 2).
PSPC B showed two degradation effects after about 10 months of continuous operation. A spot with an increased count rate of 10^{-2} cts s^{-1}mm^{-2} showed up at the edge of the sensitive area. In addition, the whole background in the image increased from 10^{-1} cts s^{-1} to 2×10^{-1} cts s^{-1}. The increased background was caused by delayed signals of small amplitude occuring after background events or X-ray events in the higher energy band. The delay time between the main signal and the low-amplitude signal was between 150 μs and 500 μs. This effect varied for the three gas supply tanks of the payload and in addition it was also dependent on the pressure status of the tank. Using tank 2 and 3 for the gas supply of the detector, the background count rate increased, when the tank pressure has dropped by a factor of two (200 bar filling pressure). Using the gas from tank 1, the background did not increase for the complete gas filling. All tanks went through the same cleaning procedure. Separate analysis of the gas quality of the three tanks before launch showed identical values for contaminations like O_2, H_2O, N_2 and Kr below 1ppm. The reason for a cleaner gas in tank 1 is probably a more frequent use of this tank during ground tests. The increased background count rate of the PSPC could be reproduced on the ground with a spare unit of the PSPC by adding more than 10 ppm of H_2O to the detector gas. Outgassing of the supply tanks could cause such a contamination. Why it showed up at half of the filling pressure of the tank is not understood.

When the increased background count rate and the warm spot showed up in the redundant PSPC B, we decided to reduce the anode high voltage of the detector by about 50 V. With a 27% reduced gas gain we operated PSPC B for another 2.5 years without problems until the gas supply was nearly exhausted (Fig.4 periods 3-5). During period 4 (Fig.4) the gas flow rate was reduced by a factor of two causing a drop in gain and a steeper gain decay. The reason for

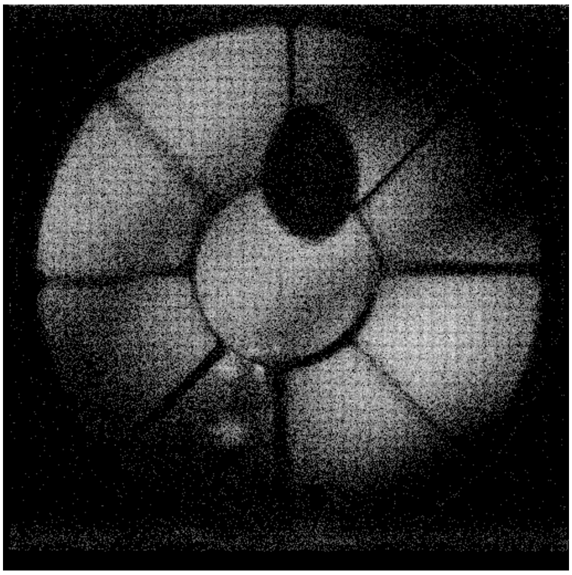

Fig. 5. Final X-ray image of the PSPC. The quasi-flat field illumination was created by moving the calibration sources in steps across the window. The egg-shaped dark spot is the area with reduced gas gain.

the gain step is the reduced gas flow rate in conjunction with the differential gas diffusion through the thin window, giving rise to a change in detector gas composition. The steeper gain decay is caused by the stronger accumulation of contaminants with a reduced gas flow. This can be seen during period 5 when the detector was operated only for short observations with a gas flow rate as in period 4, but with a reduction of the detector pressure to 200 mbar during non-operative time. By this process the detector gas became cleaner and the gain recovered to the original values as in period 3. A complete evacuation would have been more effective, but the minimum pressure of 200 mbar had to be maintained to prevent the detachment of the window foil from the support grid, which could cause a leakage of the foil. After period 5, the gas supply of the PSPC was nearly exhausted. From that time on the observations were carried out with the HRI and the PSPC was used only for special observations during short periods. During these periods (7, 8, 9) we reduced the gas flow by a factor of 20 to extend the mission as long as possible. The tank pressure had dropped already so far that there was no monitoring in the housekeeping data. This low gas flow rate gave rise to a gain drop of about 10% in two weeks. At the end of the mission, after more than eight years, a final observation with the PSPC was carried out. The observation was a moon occultation of Sco X-1 to measure the dust scattering halo of this source. The observation was time-critical and could only be made at the border of the radiation belts. The observation succeeded, but during this time the PSPC suffered probably a discharge in the high charged-particle flux environment. An increasing area with a 50% gas gain drop developed within several days (Fig.5).

4 Results of the ROSAT mission

With more than eight years of active observing time, ROSAT has been so far the most fruitful X-ray astronomy observatory. The ROSAT mission increased

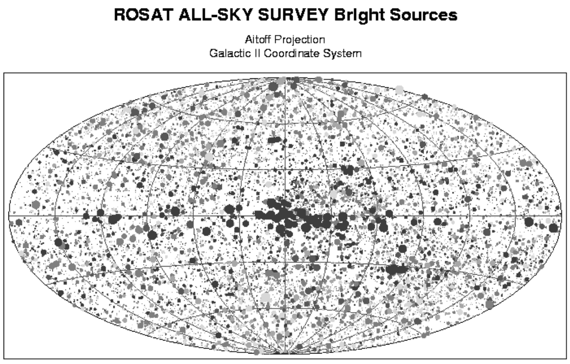

Fig. 6. Bright-source X-ray map of the sky measured by ROSAT [3].

the number of known celestial X-ray sources from several 10^3 to more than 10^5 (Fig.6). But ROSAT not only contributed to the number of known sources. Due to the high background rejection efficiency and the good energy resolution of the PSPC, four colour X-ray images of all types of objects could be measured with high contrast. Until now, sky survey data and pointed observation data of ROSAT led to more than 4500 scientific publications.

5 Acknowledgements

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Figure 1
Schematic diagram of the grid system of the PSPC.
Figure 2
Integrated Detector. On top of the detector housing is a filter wheel with four positions: open, closed, Boron filter and vacuum door with three calibration sources.
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Flat field illumination of the central part of the PSPC window with 0.93 keV X-rays. The shadows of the star-shaped window support structure and the 100 μm support wires demonstrate the imaging capabilities of the PSPC.
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Final X-ray image of the PSPC. The quasi-flat field illumination was created by moving the calibration sources in steps across the window. The egg-shaped dark spot is the area with reduced gas gain.
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