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**Non-thermal X-ray emission from Anomalous X-ray Pulsars**

den Hartog, P.R.

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*Citation for published version (APA):*

den Hartog, P. R. (2008). Non-thermal X-ray emission from Anomalous X-ray Pulsars

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# Chapter 2

## INTEGRAL

This thesis is motivated by the surprising discovery of hard X-ray emission from Anomalous X-ray Pulsars in data obtained with ESA's INTEGRAL. The space observatory INTEGRAL is dedicated to fine imaging and fine spectroscopy in the hard X-ray/soft gamma-ray band. The imager IBIS and the spectrometer SPI onboard INTEGRAL have large fields of view allowing for deep observations creating high quality sky maps and high quality spectra in the  $\sim 20$  keV to  $\sim 8$  MeV energy range. Its scientific objectives are to explore the most energetic phenomena in the universe.

In order to study the broad-band high-energy emission from AXPs archival data from other space missions have been used, especially from NASA's RXTE and ESA's XMM-Newton. At the end of this chapter RXTE and XMM-Newton are shortly introduced.

## 2.1 The INTEGRAL mission



**Figure 2.1:** Artist impression of the INTEGRAL spacecraft. Image credits ESA.

ESA's *INTErnational Gamma-Ray Astrophysical Laboratory* (INTEGRAL; Winkler et al. 2003, see Fig. 2.1) was launched from Baikonur in Kazakhstan on October 17, 2002 with a Russian PROTON rocket. The highly elliptical orbit is optimized for long uninterrupted observations (Eismont et al. 2003). The orbital period is 72 hours and from this orbit INTEGRAL can observe the sky for about 90% of this time. The rest of the time (near perigee) INTEGRAL is within the Earth's radiation belts. The nominal lifetime of INTEGRAL was two years with possible extensions up to five years. In October 2007 the fifth birthday of INTEGRAL was celebrated with a scientific workshop on Sardinia in Italy. Soon thereafter (November 2007), ESA's Science Programme Committee (SPC) unanimously approved the extension of the mission operations until the end of 2012.

### 2.1.1 The payload of INTEGRAL

The payload of INTEGRAL consists of two main telescopes and two monitors. The two main telescopes are the *Imager on-Board the Integral Spacecraft* (IBIS; Ubertini et al. 2003) and the *SPECTrometer aboard Integral* (SPI; Vedrenne et al. 2003). The two monitors are the *Optical Monitoring Camera* (OMC; Mas-Hesse et al. 2003) and the *Joint European X-ray Monitor* (JEM-X; Lund et al. 2003).

In this work we used data collected with IBIS and SPI. Both telescopes – as well as the monitor JEM-X – are coded-mask telescopes. In the (hard) X-ray energy band the only possibility to image large sky areas with good spatial resolution is with coded-mask telescopes. Especially in the hard X-ray band a large FOV is important as the count rates from individual sources are generally low. A coded mask is basically a shield with a pattern of open and closed elements designed specifically for an optimal performance in combination with the design of the detector. The sizes of the mask elements and detector elements in combination with the distance of the mask to the detector plane determine the basic characteristics of the telescope like the FOV and spatial resolution. The main difference with focused imaging is that the recorded image is a convolution of the sky image with the mask pattern. Each source will project a mask pattern on the detector plane. From the shifts and intensity differences of these projections all information about the positions and brightnesses of the sources in the FOV can in principle be decoded. The deconvolution of the patterns to the sky image is a time consuming process, especially if there are many sources in the FOV. How many sources can be discriminated in one observation/pointing depends strongly on the number and size of the open mask elements and the spatial resolution (size and number of pixels) in the detector plane. Unfortunately, the deconvolution process is not perfect. ‘Ghost sources’ can appear in the sky image especially for very bright sources and for sources in the so-called partially coded FOV. Bright sources can cause side-lobe effects. Far off-axis sources project only part of the mask on the detector (because of the limited size of the detector) and therefore they are in the partially coded FOV. In general, ghost sources can appear due to multiple solutions of the decoding. In both cases (very) detailed response modeling of the mask with its support structure as well as the detector plane suppresses many of the artefacts. This detailed modeling is of utmost importance as the smallest residuals due to imperfect modeling will become apparent in the deep imaging studies performed by INTEGRAL.

For each energy domain and/or for different science objectives a different kind of mask is required. IBIS (accurate imaging for hard X/soft gamma rays) and SPI (accurate spectroscopy for hard X-ray and gamma rays) are sensitive to high-energy photons. They have masks which are 1.6 cm and 3 cm thick, respectively. The mask of IBIS is a large  $1.064\text{m} \times 1.064\text{m}$  mask with small  $11.2\text{mm} \times 11.2\text{mm}$  elements. SPI has a circular mask of 78 cm in diameter with 127 large elements. The monitor JEM-X (accurate imaging for soft X-rays) has a thin mask of only 3.3 mm with a diameter of 535 mm and 22501 elements. The fractions of open elements are  $\sim 50\%$  for IBIS and SPI and 25% for JEM-X. See e.g. in’t Zand (1992) or Skinner & Ponman (1994) for more information about coded masks and imaging techniques.

### 2.1.1.1 IBIS

The *Imager on-Board the Integral Spacecraft* (IBIS; Ubertini et al. 2003) is the telescope most used in the work for this thesis. IBIS is sensitive over a broad energy range from  $\sim 18$  keV up to  $\sim 2$  MeV. The fully coded FOV is  $9^\circ \times 9^\circ$  and the partially coded FOV (zero response) is  $29^\circ \times 29^\circ$ . The detector area of IBIS consists of two detector layers. The top layer, *Integral's Soft Gamma-Ray Imager* (ISGRI; Lebrun et al. 2003), is optimized in sensitivity for the energy range  $\sim 18$  keV up to  $\sim 300$  keV. The bottom layer, *Pixellated Imaging CaeSium Iodide Telescope* (PICsIT; Labanti et al. 2003; Di Cocco et al. 2003), becomes more sensitive than ISGRI above  $\sim 200$  keV. The optimum sensitivity of PICsIT is in the range from  $\sim 175$  keV to  $\sim 2$  MeV.

ISGRI has a CdTe detector array of  $128 \times 128$  elements which has a continuum sensitivity of  $\sim 3.7 \times 10^{-7}$  ph cm $^{-2}$  s $^{-1}$  keV $^{-1}$  ( $3\sigma$ ,  $10^6$  s at 100 keV). It has a sensitive area of 2600 cm $^2$ . With an angular resolution of  $12'$  and a point-source location accuracy of less than  $1'$  for a  $10\sigma$  source, this instrument is the highest-resolution hard X-ray imager launched to date. ISGRI is also excellent for timing studies with a relative timing accuracy of  $61 \mu\text{s}$  and an absolute timing accuracy of  $90 \mu\text{s}$  (Kuiper et al. 2003).

The detector of PICsIT is composed of an array of  $64 \times 64$  CsI(Tl) crystals and has a sensitive area of 2890 cm $^2$ . The angular resolution is  $12'$  with a point-source location accuracy of  $5'$  (for a  $10\sigma$  source). However, imaging studies with PICsIT are very difficult due to a high cosmic-ray-induced background level. This background level cannot be suppressed in the analysis on ground, because the INTEGRAL telemetry does not allow the transmission of the high rate of single events. Sophisticated imaging software is being developed, but is not yet applicable to the analysis of very long observations of weak sources performed in this thesis. The spectral timing mode gives the opportunity to perform timing studies in 4–8 energy bands with a time resolution between 0.97–62.5 ms (depending on the settings throughout the years).

Data from IBIS-ISGRI are used in every chapter of this thesis. In Chapter 3 a survey of the Cassiopeia region is presented which is indicative of what can be achieved with spectral-imaging analysis with ISGRI. From Chapter 4 and onwards also timing analysis is performed on IBIS data.

### 2.1.1.2 SPI

The *SPectrometer aboard Integral* (SPI; Vedrenne et al. 2003) is sensitive between  $\sim 20$  keV up to  $\sim 8$  MeV and optimized for high-resolution spectroscopy. Its energy resolution is excellent with 2.5 keV at 1.33 MeV. SPI has a fully coded FOV is  $16^\circ$  and a partially coded FOV of  $31^\circ$ . The detector array consists of 19 hexagonal high-purity n-type germanium detectors with a sensitive area just over 500 cm $^2$ . The limited number of detectors and the large open mask elements result in a very modest  $2.5^\circ$  angular resolution. The point-source positioning accuracy is  $10'$  (for a  $10\sigma$  source). SPI becomes equal/more sensitive than IBIS-ISGRI above  $\sim 200$  keV. In this work SPI is used in Chapters 6 and 7.

### 2.1.1.3 The monitors

Onboard INTEGRAL there are two monitoring telescopes the *Optical Monitoring Camera* (OMC; Mas-Hesse et al. 2003) and the *Joint European X-ray Monitor* (JEM-X; Lund et al. 2003).

The OMC is basically a small classic lens telescope. The focal length is 153.7 mm ( $f/3.1$ ) with an aperture of 50 mm. Its Field Of View (FOV) is just below  $5^\circ \times 5^\circ$ , which fits within the FOV of JEM-X. It operates in the visible (V) band and it has a limiting magnitude of  $m(V) \approx 17.4$  for 5000 s for the Galactic plane and  $m(V) \approx 18.2$  for a low-background region. The OMC is useful to simultaneously monitor the optical counterparts of the X-ray sources.

The JEM-X monitor consists of two units oriented to the center of the FOVs of IBIS and SPI in order to extend the spectral range to lower X-ray energies. JEM-X is sensitive over the energy range  $\sim 3$  keV to  $\sim 30$  keV, well overlapping with the energy window covered by IBIS, which starts around 18 keV. JEM-X has a  $13^\circ 2'$  FOV (zero response). Each unit has a micro-strip gas chamber which is filled with a mixture of Xenon and Methane and has a sensitive area of  $500 \text{ cm}^2$ . The angular resolution is  $3.3'$  with a point-source location accuracy of  $15''$  (for a  $10\sigma$  source). Only one unit is used at a time. JEM-X is useful for extending the spectral range of the observed (brighter) hard X-ray sources and also for simultaneous time variability studies.

## 2.2 RXTE and XMM-Newton

The *Rossi X-ray Timing Explorer* (RXTE) is NASA's currently operational X-ray timing mission. It has been operational since 1996. Onboard RXTE are two non-imaging X-ray instruments and one imaging monitor. The non-imaging instruments are the Proportional Counter Array (PCA; Jahoda et al. 1996) and the High Energy X-ray Timing Experiment (HEXTE Rothschild et al. 1998). The monitor is called the All-Sky Monitor (ASM Levine et al. 1996).

The PCA is sensitive between  $\sim 2$  keV and  $\sim 60$  keV and consists of five collimated xenon proportional-counter units (PCUs) with a total effective area of  $\sim 6500 \text{ cm}^2$ . The FOV of the PCA is  $\sim 1^\circ$  (FWHM). Each PCU has a front Propane anti-coincidence layer and three Xenon layers. The maximum time resolution is  $\sim 1 \mu\text{s}$  with an absolute timing accuracy of  $\sim 5\text{--}8 \mu\text{s}$ .

HEXTE is sensitive between  $\sim 15$  keV and  $\sim 250$  keV and consists of two independent detector clusters, each containing four Na(Tl)/ CsI(Na) scintillation detectors. The collecting area is  $1400 \text{ cm}^2$  and the FOV is collimated to  $\sim 1^\circ$  (FWHM). The maximum time resolution is  $\sim 7.6 \mu\text{s}$ .

Also onboard RXTE is the All-Sky Monitor (ASM; Levine et al. 1996). The ASM consists of three scanning shadow cameras with slit coded masks. The detectors are position-sensitive proportional counters which are sensitive in the energy range 1.5–12 keV. Each unit has a FOV of  $6^\circ$  by  $90^\circ$  (FWHM).

*XMM-Newton* (Jansen et al. 2001) is ESA's currently operational X-ray mission which has been operational since 2000. In this work data from the EPIC-PN (European Photon Imaging Camera) camera (Strüder et al. 2001) has been used. It has an effective area of  $\sim 1000 \text{ cm}^2$  with a maximum FOV of  $\sim 30'$ , depending on the observing mode. The EPIC-PN consists of a  $6 \text{ cm} \times 6 \text{ cm}$  CCD array sensitive for X-rays in the energy range  $\sim 0.3\text{--}12 \text{ keV}$ . The camera has an angular resolution of  $\sim 6''$  and a point-source location accuracy of  $\sim 1''5$ . Its maximum time resolution ranges from 0.03 ms in the burst mode to 200 ms in the extended-full-frame mode.

To support the INTEGRAL studies, data from RXTE and *XMM-Newton* have been used throughout this work.