Prospects for the INTEGRAL Spectrometer SPI

V. Schönfelder

Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse, D-85740 Garching, Germany

Abstract. The main scientific goal of the Spectrometer SPI aboard ESA's INTEGRAL Mission will be to perform high-resolution gamma-ray line spectroscopy. The performance capabilities of SPI and its scientific prospects are summarized.

1. Introduction

INTEGRAL is the next major step in gamma-ray astronomy after the French-Soviet mission SIGMA and NASA's Compton Gamma-Ray Observatory (CGRO). INTEGRAL is the 'medium-size mission M2' of ESA, which is to be launched in 2001 – probably by a Russian PROTON-rocket. It will be an observatory-type mission with most of the observation time devoted to the scientific community. Only a relatively small fraction will go to the instrument teams (Winkler 1997).

INTEGRAL was designed by ESA in such a way that its observations will complement those made by the earlier missions. This complementarity is focussed on four aspects:

First, on high-resolution spectroscopy. This research field will be the main topic of the 'Spectrometer INTEGRAL' (SPI). Though the Compton Observatory – especially COMPTEL – really achieved a break-through in gamma-ray line spectroscopy and showed that the sky is rich in this field, none of the instruments aboard CGRO was able to measure the profiles of gamma-ray lines. SPI will perform such measurements.

IBIS (the **I**mager on **B**oard **I**NTEGRAL **S**atellite) will focus on the second aspect, namely high-spatial resolution. The instruments aboard CGRO had angular resolutions of the order of 1 degree or worse. IBIS' angular resolution of 12 arc minutes will hopefully lead to the identification of many so far unidentified sources. Though SIGMA had a resolution comparable to that of IBIS, IBIS will be about twenty-times more sensitive than SIGMA.

The third aspect of complementarity is the possibility to perform simultaneous observations of the gamma-ray sources with two monitors: an X-ray monitor (JEM-X), and an optical monitor camera (OMC).

The fourth aspect, finally, is focussed on the capability to discover and react to transient gamma-ray source events. From previous missions we have learnt that the gamma-ray sky is continuously changing. Gamma-ray sources suddenly appear and then disappear again. On INTEGRAL, a weekly 'Galactic Plane Scan Mode' will be introduced to discover new transient source events.

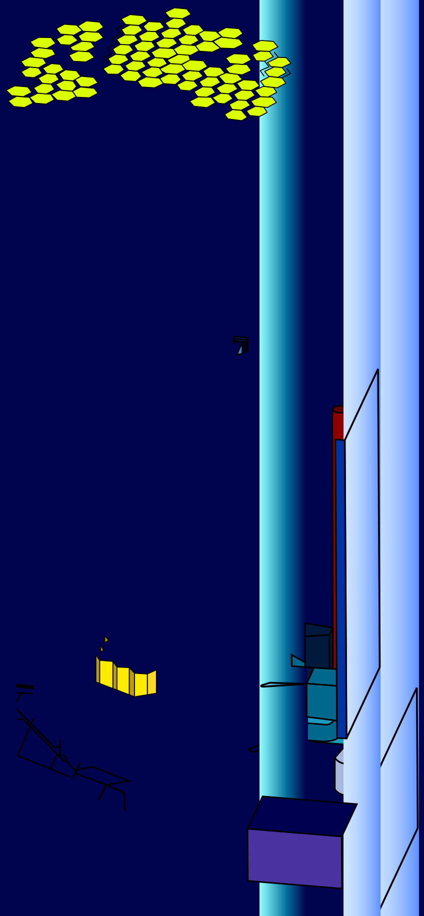

Figure 1. Schematic view of SPI.

In the rest of this paper I shall focus on the Spectrometer SPI, on its performance capabilities and on its scientific prospects.

2. Performance Characteristics of the Spectrometer INTEGRAL

Detailed descriptions of SPI exist in the literature (see e.g. Lichti et al. 1996; Mandrou et al. 1997).

SPI consists of three main elements: an hexagonal array of 19 cooled germanium detectors (thickness: 7 cm, side length 3.2 cm), a hexagonal passive mask with 127 elements (63 elements opaque (3 cm tungsten) and 64 elements transparent) mounted 171 cm above the detector array, and a massive anticoincidence shield made of BGO-scintillation crystals (effective shielding thickness: ~ 5 cm) (see Fig. 1). The germanium detector array and the tungsten mask are operated as a coded aperture mask telescope.

The main required performance parameters of SPI are summarized in Table 1:

Table 1. Required Performance Parameters of SPI

Energy range	20 keV – 8 MeV
Energy resolution	2 keV at 1 MeV
Angular resolution	$\sim 2^\circ$
Fully coded field-of-view	16°
Timing accuracy	100 μ sec
Narrow line sensitivity	$5 \cdot 10^{-6}$ cm^{-2} sec^{-1} at 1 MeV $2 \cdot 10^{-5}$ cm^{-2} sec^{-1} at 511 keV

These required performance parameters affected the design of SPI in the following way:

1. The required energy resolution implied the use of cooled (85 K) germanium detectors.
2. The angular resolution of SPI is determined by the pixel-size of both the germanium detector array and the mask, and by the distance between both. Since the germanium detector assembly consists of only 19 detectors, an image of the sky is not unambiguously defined by the mask pattern. The ambiguity is resolved by introducing 'dithering'-steps of the telescope axis around the direction of the gamma-ray source to be studied.
3. The field-of-view of SPI is defined by the areas of the mask and the germanium detector assembly, and by their distance.
4. The requirement on the narrow-line sensitivity to be roughly a factor of 10 better than that achieved by CGRO is reached in two ways: first, by making the germanium detector assembly as large as possible within the constraints of INTEGRAL (500 cm^2), and second, by minimizing the background. The latter is achieved by optimizing the material (BGO), the shape and the thickness of the anticoincidence shield, by incorporating a pulse-shape discrimination technique, which separates β-decay background events from gamma-ray events, by carefully selecting special materials inside SPI, and by adding a plastic scintillator anticoincidence plate below the passive mask.
5. The absolute timing accuracy of 100 μsec requires a high telemetry rate, because the events are recorded photon-by-photon.

The three main performance characterisitics of SPI, the energy resolution, the narrow-line sensitivity and the continuum sensitivity are illustrated in Figures 2, 3, and 4.

The energy resolution – as obtained from an engineering model – is shown in Fig. 2 (from Mandrou et al. 1997). The resolution is typically 2 keV at 1 MeV (as required) and becomes slightly worse (in absolute terms) at higher energies (e.g. 3.5 keV at 6 MeV).

The narrow line sensitivity of SPI is shown in Fig. 3 (top) for two cases: first, for an observation time of 10^6 sec (nearly two weeks) and second, for the

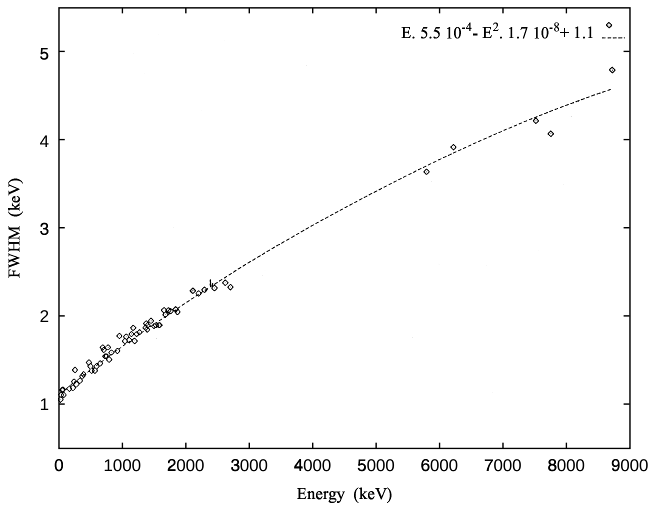

Figure 2. Energy resolution as derived from an engineering model of SPI.

end of the mission, when special regions of the sky like the central radian of the Galactic plane have been exposed in total for $4 \cdot 10^6$ sec (from Mandrou et al. 1997). These sensitivities are indeed typically ten times better than those obtained by OSSE and COMPTEL. However, this improvement is only valid for narrow lines. The bottom diagram of Fig. 3 illustrates, how the sensitivity degrades for broader lines.

In Fig. 4 the 3σ continuum sensitivity of SPI in 10^6 sec observation time is compared with that of IBIS, JEM-X, OSSE, COMPTEL and SIGMA. Generally speaking, the continuum sensitivities of SPI and IBIS are similar, and they are also comparable to the CGRO sensitivities below 3 MeV. The main continuum results of SPI will probably be obtained in the energy range below 1 MeV, where its sensitivity is 10 to 20-times higher than that of SIGMA.

3. Scientific Prospects of SPI

The main interest in SPI is based on its capability to measure gamma-ray line intensities, line profiles and line shifts with unprecedented sensitivity. The gamma-ray lines to be studied are either produced by nucleosynthesis processes or by interactions between energetic particles and nuclei.

The measurements of these lines will yield information on the creation processes, on the creation locations, and on the physical conditions under which the lines are produced. The most promising production sites are supernovae and their remnants, massive stars (like Wolf-Rayet stars), novae, accreting black hole candidates, and the interstellar medium. The interpretation of the line measurements will yield information on the abundances and spatial distributions of chemical elements or energetic particles, and on parameters like velocity, density, and temperature in the line emitting regions.

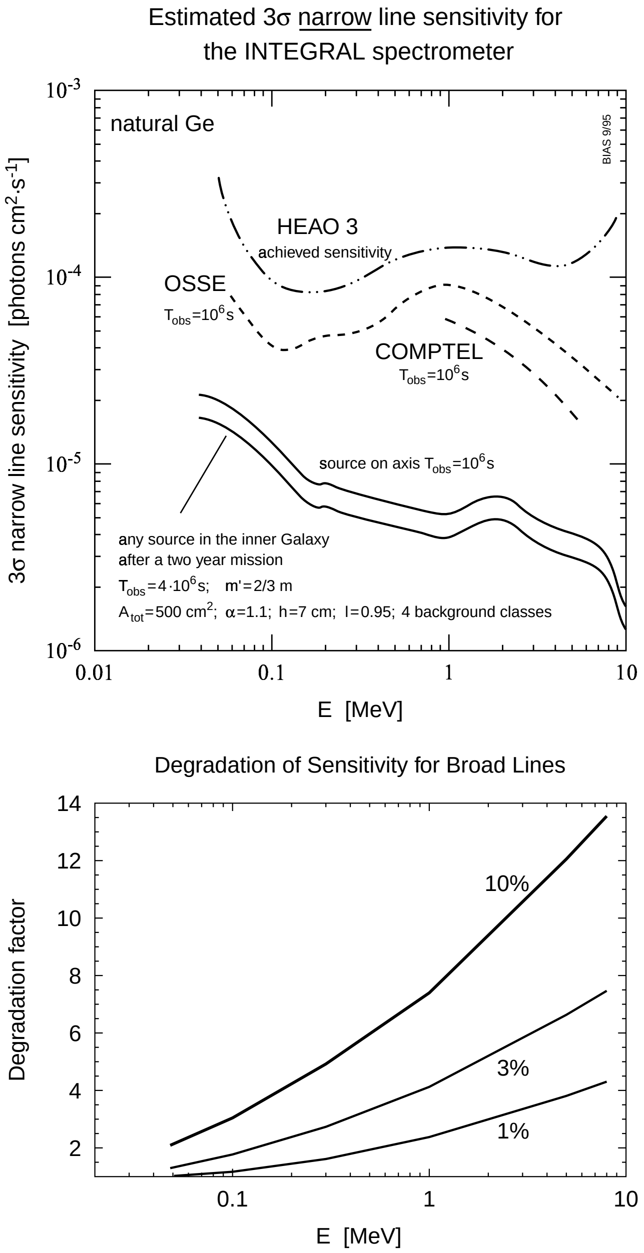

Figure 3. Top diagram: Narrow line 3σ sensitivity of SPI as a function of energy. Bottom diagram: Degradation of sensitivity for broadened lines. The degradation factor is plotted for line widths of 1 %, 3 %, and 10 % FWHM of the line energy.

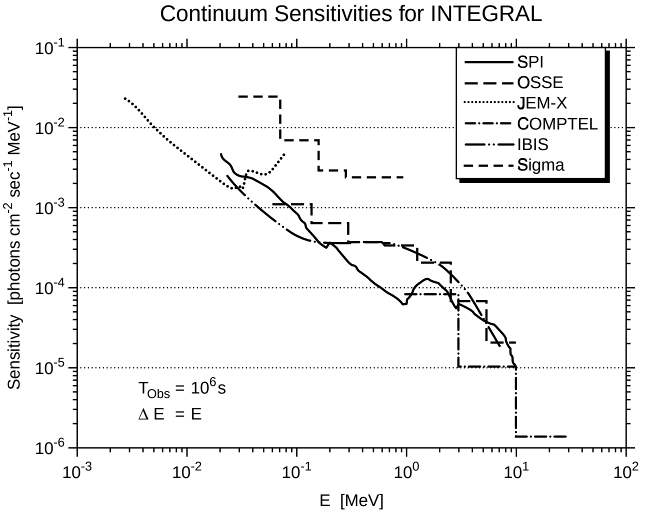

Figure 4. 3σ continuum sensitivity of SPI in comparison with that of IBIS, JEM-X, OSSE, COMPTEL and SIGMA) for an observation time of 10^6 sec.

The prime astrophysical topics to be addressed are, therefore, nucleosynthesis processes and their sites, supernova theories, nova theories, supernova and nova statistics, interstellar physics, low-energy cosmic ray physics, and pair-plasma physics in compact objects like neutron stars, stellar or massive black holes.

In the following, the prospects of SPI for the most important of these topics are summarized:

1. Supernovae

   The chance that a supernova of type Ia occurs with detectable gamma-ray line emission from the ^{56}Ni $\rightarrow$ ^{56}Co $\rightarrow$ ^{56}Fe decay chain in the INTEGRAL lifetime is not too bad. It will depend on the line broadening up to which distance a type Ia supernova can still be detected by SPI. If an expansion velocity of 10 000 km/sec is assumed, the sensitivity limit for detecting the 847 keV ^{56}Co-line is about $3 \cdot 10^{-5}$ cm^{-2} sec^{-1}. For a ^{56}Ni-yield of the supernova of 1 $M_\odot$ this results in a detectability up to a distance of 15.5 Mpc. Within this distance, one type Ia supernova can be expected every two or three years (Gehrels et al. 1987).

   The chance to detect gamma-ray line emission from a nearby type II supernova is much smaller, because of the lower ^{56}Ni-yield and the long obscuration time of type II supernovae to gamma rays.

2. Supernova Remnants

   So far, gamma-ray lines have been detected from two supernova remnants, namely Cas-A (Iyudin et al., 1997) and the recently discovered, previously unknown COMPTEL-ROSAT remnant RX J0852.0-4622 (Aschenbach 1998 and Iyudin et al. 1998). From both these remnants COMPTEL has detected the 1.157 MeV ^{44}Ti line with fluxes between (3 to 4) $\cdot 10^{-5}$ photons cm^{-2} sec^{-1}. At these flux levels, SPI will be able to measure the line profiles from both objects in a deep exposure observation. Also the simultaneously emitted hard X-ray lines at 68 keV and 78 keV shoud be well detectable by IBIS. The knowledge of the line shape will be of fundamental importance for the study of the physical conditions in the remnant. If the distance of the COMPTEL-ROSAT supernova remnant is confirmed to be as close as 200 pc, this remnant should also cause part of the 1.809 MeV ^{26}Al emission detected by COMPTEL from the Vela region (Diehl et al. 1999).

Since the central radian of the Galaxy will be deeply exposed during the INTEGRAL core program, the prospects are good to find further, so far unknown supernova remnants with SPI during these observations.

3. Interstellar ^{26}Al and ^{60}Co Line Emission

Now that COMPTEL has produced an all-sky map in the light of the 1.809 MeV ^{26}Al line (Oberlack 1998), SPI will have to address the following open questions concerning this line:

- What is the width of the line? Is it a narrow line, only smeared by the diffential rotation of the Galaxy? Or is it as broad as 5.4 keV FWHM as suggested by the GRIS balloon experiment (Naya et al., 1996).
- What are the main line emitting regions? Establishing the line maximum to within a few tens of keV may enable us to better understand the emitting regions and the features connected with spiral arms.
- Are supernovae or massive stars like Wolf-Rayet stars the main sources of ^{26}Al in interstellar space? The detection of ^{60}Co line emission by SPI from the $^{60}\text{Ni} \rightarrow {}^{60}\text{Co} \rightarrow {}^{60}\text{Fe}$ decay chain may finally help to discriminate between these two possbilities. Wolf-Rayet stars are not expected to show ^{60}Co line emission. If the ^{26}Al and ^{60}Co distributions are similar, then their origin should be in supernovae.

4. 511 keV Annihilation Line from Interstellar Space

The 511 keV annihilation line in interstellar space has been extensively studied by OSSE. Its distribution in the Galaxy consists of an extended disk component and a bulge component. Within the bulge component a fountain feature 7 degree north of the Galactic center was possibly found (Purcell et al. 1997). SPI will be able to measure the spatial distribution of the line at least within the Galactic central radian, search for the fountain and measure the line width in the different disk components thus giving information about the physical state of the interstellar gas in which the positrons annihilate. Also, the contribution from other positron emitting point sources to the 511 keV emission of the interstellar medium will be addressed by SPI.

5. Novae

   Gamma-ray lines from classical novae have not yet been detected so far. Most promising are the lines from the ^{7}Be $\rightarrow$ ^{7}Li decay at 478 keV and from the ^{22}Na $\rightarrow$ ^{22}Ne decay at 1.275 MeV. For typical expansion velocities of a nova of 2000 km/sec the line broadening will be 1.5 % FWHM, i.e. 7.5 keV FWHM for the 478 keV line, and 20 keV FWHM for the 1.275 MeV line. The sensitivity limit of SPI for such line widths is about $1 \cdot 10^{-5}$ photons cm^{-2} sec^{-1}. Probably novae must be closer than 1 kpc to become visible these lines. The evolution of the line width with time will allow detailed studies of the dynamics of novae.

6. Nuclear Interaction Lines from Interstellar Space

   After the revision of the COMPTEL results on nuclear interaction line emission from Orion (Bloemen 1999), the intensity level at which nuclear interaction lines can be expected from the interstellar medium is entirely open again. The 'narrow' line components from excited ^{12}C* and ^{16}O* nuclei at 4.4 MeV and 6.1 MeV (produced by the bombardment of these nuclei with energetic protons) are typically 100 keV broad. The SPI sensitivities for such lines from a point-like source region will be about $1.5 \cdot 10^{-5}$ cm^{-2} sec^{-1} (see Fig. 3) and the sensitivity limit for the detection of these lines from the interstellar medium within the central radian of the Galaxy will be typically $1 \cdot 10^{-4}$ photons cm^{-2} sec^{-1} rad^{-1}, which is comparable to the COMPTEL sensitivity limit.

In addition to the gamma-ray line measurements described so far, SPI will certainly also make important contributions to continuum measurements in the sub-MeV range, especially from compact objects such as X-ray binaries with neutron stars or stellar black-hole candidates or from active galactic nuclei. SPI will also be able to measure the spatial distribution of the diffuse Galactic continuum gamma-ray emission from the interstellar medium below 1 MeV. The origin of this emission is not well understood (see Strong and Moskalenko 1999). Whereas most of the emission at higher energies can be reasonably well understood as the sum of π^o-decay gamma rays, relativistic bremsstrahlung emission and inverse Compton emission from energetic cosmic ray particle interactions, an additional component must exist in the sub-MeV range, which may be either bremsstrahlung emission from an additional low-energy cosmic ray electron component or due to so far unresolved point sources. SPI might be able to address this question. It is well capable of producing images of the extended continuum emission in the sub-MeV range (Strong et al. 1999).

4. Conclusion

Due to its high narrow line sensitivity, SPI will certainly make a major step forward in the field of gamma-ray line spectroscopy. Much progress will be especially achieved in the area of nucleosynthesis lines. On the other hand it remains unclear whether SPI will succeed in the detection of gamma-ray lines from energetic particle interactions in interstellar space.

References

Aschenbach, B. 1998, Nature, 396, 141-142

Bloemen, H. 1999, These Proceedings

Diehl, R. et al. 1999, Proc. of 3rd INTEGRAL Workshop, Taormina 1998, Ed.: G. Palumbo, A. Bazzano, and C. Winkler, Astrophys. Letters and Communications, 1999, in press

Gehrels, N., Leventhal, M., and MacCallum, C.J. 1987, ApJ, 322, 215

Iyudin, A. et al. 1997, Proc. of 2nd INTEGRAL Workshop, ESA-SP-382, p. 37-41

Iyudin, A. et al. 1998, Nature, 396, 142-144

Lichti, G. et al. 1996, SPIE-Proceedings, eds.: B.D. Ramsey and T.A. Parnell, Vol. 2806, p. 217-233 Mandrou, P. et al. 1997, Proc. of 2nd INTEGRAL Workshop at St. Malo, ESA-SP-382, p. 591-598

Oberlack, U. 1998, PhD-Thesis, Technical University Munich, Physics Department 'Über die Natur der galaktischen ^{26}Al-Quellen Untersuchung des 1,8-MeV-Himmels mit COMPTEL'

Naya, J.E. et al. 1996, Nature, 384, 44

Mandrou et al. 1997, Proc. of 2nd INTEGRAL Workshop at St. Malo, ESA-SP-382, p. 591-598

Purcell, W.R. et al. 1997, ApJ, 491, 725

Strong, A. et al. 1999, Proc. of 3rd INTEGRAL Workshop, Taormina 1998, Ed.: G. Palumbo, A. Bazzano, and C. Winkler, Astrophys. Letters and Communications, 1999, in press

Strong, A. and Moskalenko, I. 1999, These Proceedings

Winkler, C. 1997, Proc. of 2nd INTEGRAL Workshop at St. Malo, ESA-SP-382, p. 573-580