SPI Cosmic Radioactivity Measurements in Perspective

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The ESA-Mission INTEGRAL (International Gamma-Ray Astrophysics Laboratory) is the next step in low-energy gamma-ray astronomy (up to 10 MeV) and will be launched in 2002. The spectrometer SPI – one of its two main instruments – is dedicated to high-resolution line spectroscopy (ΔE = 2.5 keV FWHM at 1.3 MeV). SPI will concentrate on the study of lines from radioactive isotopes. A wealth of new information is expected from interstellar line emission with narrow line profiles, but exciting results are also expected from line profile measurements of individual line emitting objects such as supernovae, supernova remnants, and novae.

1. Introduction

The International Gamma-Ray Astrophysics Laboratory (INTEGRAL) of ESA will be the next step in space-borne gamma-ray astronomy after the successful missions of SIGMA on GRANAT and the Compton Gamma-Ray Observatory. INTEGRAL will be devoted to high-resolution spectroscopy and fine source imaging in the energy range 15 keV to 10 MeV, and in addition, will allow parallel monitoring of the observed gamma-ray sources in the neighbouring X-ray band and at optical wavelengths [14,15].

INTEGRAL was selected in 1993 as a Medium Size Mission of the ESA programme. It is worth mentioning that the present concept of INTEGRAL differs somewhat from that proposed to ESA in 1993. Most of the changes were made after it became clear that a major involvement of the US could not be realized and after the UK decided not to participate in the building of the scientific payload.

INTEGRAL is expected to be launched in 2002 by a Russian PROTON rocket, which will bring the laboratory into a 72 hour elliptical orbit (inital perigee 10 000 km, apogee: 153 000 km) of 51.6° inclination. The nominal mission life time will be 2 years. An extension by three additional years is possible. INTEGRAL will be operated as an observatory: most of its observation time will be made available to the scientific community.

In the following, first, a description of the payload, the expected sensitivities in line and continuum emission, and the observation program are given. The second part of the paper deals with expectations from radioactivity measurements with SPI.

2. The Scientific Payload

INTEGRAL will carry four instruments: the two main instruments SPI and IBIS, and the two monitors JEM-X and OMC.

SPI (20 keV to 8 MeV) will be devoted to high-resolution spectroscopy with modest imaging. Within its fully coded field-of-view of 16° FWHM, its angular resolution is about 2.5° FWHM [18]. SPI will build upon the results which OSSE and COMPTEL obtained in the field of gamma-ray line spectroscopy. It will be able to measure the profiles of gamma-ray lines to an accuracy of about 2 keV. This is its most important aspect. The knowledge of the line profile allows a detailed study of the physical conditions of the sky regions in which the lines are produced, like temperature, expansion velocity, ionization degree, and emission geometries. A similar experiment (called GRSE) was originally planned for the Compton Gamma-Ray Observatory, but was never realized.

The imager IBIS (15 keV to 10 MeV) will have an excellent angular resolution of 12 arc min within its fully coded field-of-view of 9° FWHM [17]. IBIS may be considered as the follow-on step

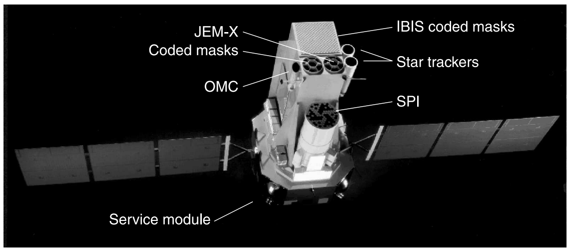

Figure 1. Schematic View of INTEGRAL.

after SIGMA on GRANAT, which had practically the same angular resolution, but which was less sensitive by about a factor of 10.

The two monitor instruments will allow parallel monitoring of the gamma-ray sources in the adjacent X-ray band and at optical wavelengths. JEM-X (3 keV to 35 keV) has an excellent angular resolution of 3 arc min in its 4.8° FWHM field-of-view [9]. The optical monitor camera OMC (500 to 600 nm) has a pixel resolution of 16.6 arc sec within its 5.0° x 5.0° field-of-view [3].

SPI, IBIS and JEM-X are all based on the coded aperture imaging technique. SPI uses germanium detectors, IBIS CdTe and CsI detectors, and JEM-X microstrip Xenon gas detectors. OMC consists of a passively cooled CCD in the focal plane of a 50 mm lens.

3. The INTEGRAL Sensitivities

The scientific return of the INTEGRAL mission will mainly depend on the sensitivities of its instruments. The actual sensitivities will only be known after launch, when the in-orbit background is known. Much effort has been invested to predict the background from previous missions.

Figure 2 shows the expected 3σ narrow line sensitivity of SPI and IBIS for an observation time of 10^6 sec in comparison with that of HEAO-3 and COMPTEL and OSSE on the Compton Gamma-Ray Observatory. The term "narrow" is defined to be identical to the energy resolution of the instruments (2.5 keV FWHM for SPI at 1.3 MeV, about 6 to 7 % FWHM for IBIS, 3 keV FWHM for HEAO-3, 10 % FWHM for COMPTEL, and 5 to 6 % FWHM for OSSE).

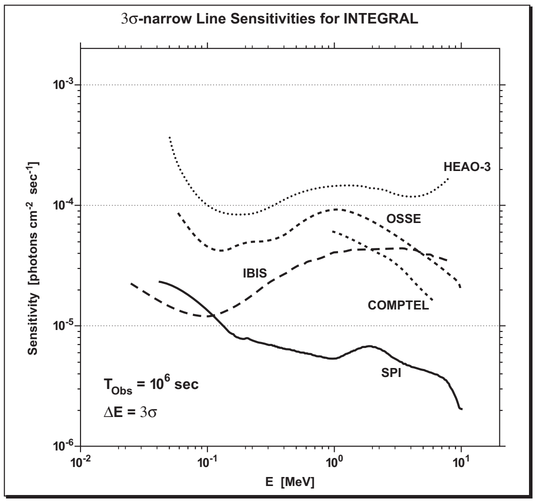

Figure 2. Point source sensitivity (3σ) for narrow line detections with SPI and IBIS for 10^6 sec observation time in comparison with the sensitivities of HEAO-3, OSSE, and COMPTEL.

For broadened gamma-ray lines, the SPI sensitivity is somewhat degraded. The dependence of the degradation factor on the width of the line is illustrated in Fig. 3.

The IBIS, SPI and JEM-X 3σ continuum sensitivities (for an observation time of 10^6 sec and for an energy interval $\triangle E = E/2$) are shown in Fig. 4, and are compared with the SIGMA sensitivity. Below 1 MeV, the point source detection sensitivity is in the range between 0.5 to 20 m Crab strengths. Above 1 MeV, SPI and IBIS have comparable sensitivities (at the 100 m Crab level).

4. Astrophysics with INTEGRAL in Perspective

Considering the improvements in sensitivity - as illustrated in Fig. 2 and 4 - the most important and spectacular results from INTEGRAL can be expected in the field of gamma-ray line spectroscopy and in the study of continuum gamma-ray sources in the sub-MeV range. The key objects to be studied by INTEGRAL will be

compact objects (like neutron stars, stellar black hole candidates, high-energy transients (X-ray novae), galactic micro-quasars, and gamma-

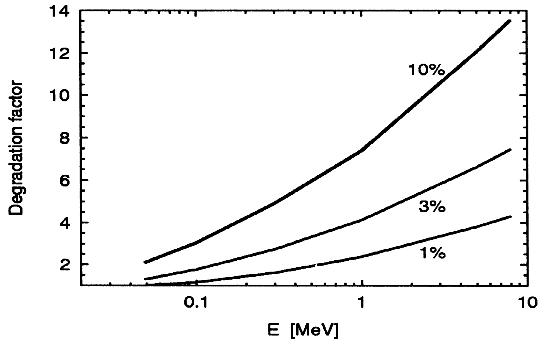

Figure 3. Degradation of SPI sensitivity for broadened lines. The degradation factor is plotted for line widths of 1 %, 3 %, and 10 % FWHM of the line energy.

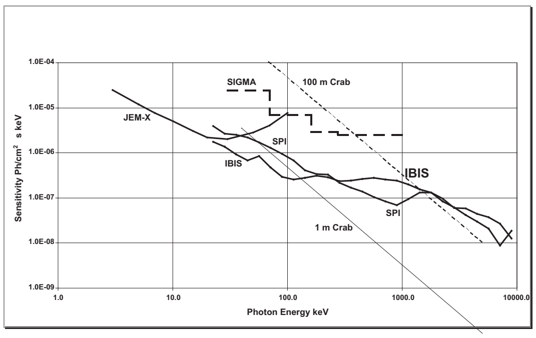

Figure 4. INTEGRAL continuum sensitivity (3σ) for an observation time of 10^6 sec and energy bins $\triangle E = E/2$ in comparison with the SIGMA sensitivity.

ray bursters), **stellar nucleosynthesis sites** (especially novae, supernovae, supernova remnants, but also hydrostatic nucleosynthesis sites like AGB and Wolf-Rayet stars), **the interstellar medium** (in continuum and gamma-ray line emission), **the Galactic center region**, **external galaxies** (especially Seyfert galaxies and gamma-ray blazars), **the cosmic gamma-ray background** (its spectral and spatial structure), **the unidentified gamma-ray sources** (especially from the EGRET source catalogue).

SPI's main research field is that of gamma-ray line spectroscopy. For IBIS Galactic binaries with compact objects like neutron stars, black-hole candidates, and transients are of special interest. In the field of gamma-ray bursts 10 to 20 events will be detected within the fields-of-view of SPI and IBIS each year.

5. The Observation Program

In the first year of the mission 65 % of the INTEGRAL observation time will be awarded to the scientific community in general (this is called the "open time"). The remaining fraction will be reserved for the INTEGRAL Science Working Team (called the "Core Programme"). In later years of the mission the fraction of the open time will further increase.

The core programme is well defined and consists of three elements [16]: a deep exposure of the Galactic central radian, weekly scans of the Galactic plane, and pointed observations.

The purpose of the deep exposure of the Galactic central radian is to map the Galactic ridge in continuum and line emission, in order to perform deep imaging and spectroscopic studies in that region. For each point along the plane in the central radian, the 10^6 sec sensitivity level (shown in Fig. 2 and 4) will be achieved after the first year.

The purpose of the Galactic plane scans is to discover transient sources (like e.g. Nova Musca, [14]). For continuum sources around 100 keV the sensitivity limit of the plane scan is at the 20 m Crab intensity level for one single scan. The sum of all weekly scans over 1 year results on average in a 1-day exposure for each point along the Galactic plane, and can thus be used to build maps of the plane in continuum and line emission.

The pointed observations are of three different kinds: first, follow-up observations of transient events detected during the Galactic central radian deep exposure and the weekly Galactic plane scan; second, follow-up observations of externally triggered transient events; and third, observation of persistent sources. Candidates for the follow-up observations are X-ray novae, superluminal jet sources, supernovae, classical novae, and AGN outbursts. The time left in the Core Programme for the observation of persistent sources is only 10^6 sec. The INTEGRAL Science Team has decided to devote this time to the observation of the

Vela region, which contains several exciting and spectacular objects.

The INTEGRAL data first will arrive at the INTEGRAL Data Centre, which is located at Versoix, near Geneva. Its main task will be the data processing, quick-look analysis, instrument performance monitoring, target-of-opportunity recognition and gamma-ray burst alerts, standard science analysis, and archiving of the science data. All INTEGRAL data will be free for public use one year after release to the observers.

6. SPI Cosmic Radioactivity Measurements in Perspective

SPI's main research field is that of gamma-ray line spectroscopy. The key topics for nucleosynthesis lines are twofold: first, the study of broad-scale interstellar emission of the 1.809 MeV ^{26}Al line, the 1.17 and 1.33 MeV lines from radioactive ^{60}Fe decay, and the electron-positron annihilation line. These are all more or less narrow lines. Second, the study of individual gamma-ray line emitting objects. Here the most interesting targets are the two supernova remnants Cas A and RX 0857-46, from which COMPTEL found evidence for 1.157 MeV emission from radioactive ^{44}Ti, additional ^{44}Ti line emitting supernova remnants in the central Galactic radian, any nearby ($<$ 15 Mpc) supernova that may occur after the launch of INTEGRAL to search for ^{56}Co and ^{57}Co gamma-ray line emission, and any nearby (typically $<$ 1 kpc) classical nova to search for the 478 keV and 1.275 MeV lines from radioacive ^{7}Be and ^{22}Na decay. The gamma-ray lines from the individual objects are all expected to be broadened; the line width depends on the expansion velocities. Finally, also the search for nuclear interaction lines from interstellar space is of great interest.

A few observational aspects of these research topics are given below:

6.1. 1.809 MeV from radioactive ^{26}Al

The main task of SPI in this field will not be to repeat the production of an all-sky map. Instead, SPI is expected to find a definite answer to the question of the origin of the ^{26}Al by measuring the line profile, possible line shifts, and by studying special regions like the inner Galaxy, Cygnus, Vela, and Carina with better angular resolution than COMPTEL could do. At present, the question of the line width is totally open: the width measured by GRIS (5.4 keV FWHM) corresponds to hot ^{26}Al nuclei with velocities of 540 km sec^{-1} [11]. The limit on the linewidth measured by HEAO C ($<$ 3 keV) is in contradiction with the GRIS result [10].

It has been proposed to determine the distances of the "hot spot" regions in the 1.809 MeV COMPTEL all-sky map from shifts of the line maximum (as is done in 21cm line astronomy of neutral hydrogen). This is a very ambiteous goal: differences in rotational velocities of 50 km sec^{-1} correspond to line shifts of only 0.3 keV.

A deep study of the Vela region in the 1.809 MeV line is of special interest, because it contains the closest Wolf-Rayet star (γ^2-Velorum), and because the peak 1.809 MeV line emission in that region concides with the position of the young X-ray supernova remnant RX 0852-46. SPI is expected to clarify, whether the emission really originates from the supernova remnant or whether it comes from the molecular ridge in that part of the sky.

6.2. ^{60}Fe line emission

The final answer to the question, whether the ^{26}Al line sources are core-collapse supernovae or massive mass-loosing stars (or a mixture of both) may come from the observation of the 1.17 and 1.33 MeV lines from radioactive ^{60}Fe decay. So far, only upper limits to the line fluxes exist, which are at the 15 % level of the 1.809 MeV line flux. SPI is expected to discover the ^{60}Fe lines in the central region of the sky and to measure the line profiles. It is common belief that ^{60}Fe is produced in core-collapse supernovae. As such, the detection of ^{60}Fe line emission and a resulting skymap in the line would provide a tracer for Galactic supernova activity. Therefore, a comparison of the ^{60}Fe and ^{26}Al maps would allow to identify the supernova contribution to the ^{26}Al map. The remaining part of the ^{26}Al map would then be due to stellar wind ejection. Actually, however, this separation may not be possible, if production of ^{60}Fe nuclei by processes other than in core-collapse supernovae can take place.

6.3. Electron/positron annihilation line

OSSE has performed a large number of pointings, from which maps in the 511 keV annihilation line and in the three-photon continuum emission could be derived of the inner Milky Way. At least, two broad-band components can be identified: an extended disk and a central bulge component. The existence of a possible fountain north to the Galactic Center, which appears in the pure line map, needs confirmation [12]. At the Baltimore Gamma Ray Symposium in 2001, the OSSE team reported that the strength of the fountain is at least a factor of 5 smaller than previously thought. The disk component may be explained by ^{26}Al, ^{44}Sc, ^{56}Co, ^{22}Na positron emitters. Also shorter lived positron emitters may contribute, because the mean annihilation time in interstellar space is of the order of 10^5 years.

The bulge component is more difficult to be explained. To a small fraction it may be produced by population II-type positron emitters like ^{22}Na and ^{56}Co from type Ia SN. In addition, compact positron emitting sources may play a role as well.

We know from SIGMA that sources like Nova Muscae [4] and 1E 1740.7-2942 [2] are able to produce positrons on a short time scale of 1 day. In any case, the contribution to the bulge-annihilation line from compact sources must be small (smaller than $4 \cdot 10^{-4}$ cm^{-2} sec^{-1}).

The profile of the 511 keV line and the positronium fraction depends on the temperature, the density and the ionization degree of the medium. The most accurate measurements of the line profile are those of TGRS [5]. The linewidth of 1.8 keV FWHM and the positronium annihilation fraction of 0.94 are both consistent with the fact that the annihilation either occurs in cold molecular clouds, or in warm neutral or ionized gas. INTEGRAL will map the galactic plane and measure the line-profile all along the plane.

6.4. Gamma-ray lines from ^{44}Ti

The detection of the 1.157 MeV line from radioacitve ^{44}Ti by COMPTEL from Cas A [7] and possibly RX 0852-46 [8] needs confirmation, and uncertainties in the reported line fluxes have to be removed. Most interesting is the measurement of the line profile by SPI, from which the expansion velocity of the ^{44}Ti material can be derived. For very high exansion velocities, the detection of the line by SPI will be difficult and marginal (see Fig. 3); for $v_{exp} = 5000$ km sec^{-1} an observation time of $3 \cdot 10^6$ sec is required for a firm line detection.

IBIS and SPI, both have the capabilities to detect the simultaneously emitted lines at 67,9 and 78,4 keV, as well.

6.5. Gamma-ray lines from 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^{-1} 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.

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 to gamma rays.

6.6. Gamma-ray line emission from novae

Unambigeous detection of gamma-ray line emission from individual classical novae has not yet been accomplished (but see contribution of A. Iyudin at this workshop). Most promising are the lines from the ^{7}Be $\rightarrow$ ^{7}Li decay at 478 keV from the ^{22}Na $\rightarrow$ ^{22}Ne decay at 1.275 MeV and the 511 keV line emission from the very short ($<$ 1 day) β^+ decay of ^{13}N and ^{18}F [6].

For typical expansion velocities of novae of 2000 km sec^{-1} 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} in 10^6 sec.

Novae most be closer than 0.5 (for ^{7}Be) to 1 kpc (for ^{22}Na) to become visible within the 478 keV and 1.275 MeV lines. Hence, only typically one such nova can be expected to be seen in these lines during the mission life time of INTEGRAL. The prospects for detecting 511 keV line emission with the anticoincidence system of SPI from the short decay of the ^{13}N and ^{18}F isotopes is somewhat more promising. Because of the nearly 4 π field-of-view of the SPI shield, no re-orientation of INTEGRAL is required, and the emission can be detected inspite of its early and short appearence in the time history of the nova.

Very recently, evidence for 1.275 MeV emission from unresolved classical novae in the central bulge region of the Milky Way was found in COMPTEL data by Iyudin et al. (these proceedings). The exact spatial distribution of this component and the profile of the 1.275 MeV line will be measured by SPI during the deep exposure of the Galactic central radian.

6.7. Nuclear interaction lines from interstellar space

After the revision of the COMPTEL results on nuclear interaction line emission from Orion [1], the intensity level at which nuclear interaction lines can be expected from the interstellar medium is entirely open again. Recent predictions on the expected 3–7 MeV line flux are of order $2.5 \cdot 10^{-5}$ cm^{-2} sec^{-1} rad^{-1} [13]. The "narrow" line components from excited ^{12}O* 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 $2.5 \cdot 10^{-5}$ cm^{-2} sec^{-1} (see Fig. 2 and 3) and the sensitivity limit for the detection of these lines from the interstellar medium within the SPI field-of-view (16°) will be typically $1 \cdot 10^{-4}$ photons cm^{-2} sec^{-1} rad^{-1}, which is comparable to the COMPTEL sensitivity limit.

In principle, SPI would be well suited to measure the very sharp line components expected from interstellar dust grains, which are produced, when the excited nuclei in the dust grains come to rest before the γ-ray lines are emitted. Unfortunately, the expected line fluxes are still well below the narrow line sensitivity of SPI, and their detections would be a surprise.

7. Conclusion

In the field of gamma-ray line astronomy, SPI will concentrate on lines from radioactive isotopes. A wealth of new information is expected from interstellar line emission with narrow line profiles, but exciting results are also expected from line profile measurements of individual line emitting objects such as supernovae, supernova remnants and novae.

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