Overview about first results from the Gamma-Ray Astronomy Mission INTEGRAL

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ABSTRACT

INTEGRAL is an ESA space mission to study the sky at hard X-ray and soft gamma-ray energies. Its two main instruments SPI and IBIS cover the energy range 15 keV to 10 MeV, and are mainly devoted to high resolution spectroscopy (?E ~ 2,5 keV at 1 MeV) and fine source imaging ($\Delta\vartheta \sim 12$ arcmin), respectively. The 4 tons heavy payload was brought into an excentric orbit of 153.000 km apogee and 9.000 km perigee on October 17, 2002 by a Russian Proton rocket. After a successful performance and verification phase, the observational program started in late December 2002 by executing open-time proposals and guaranteed core-time observations. The observations concentrated mainly towards the galactic plane, and especially the inner Galaxy. Highlights from the first 18 months of the mission are results on nucleosynthesis and solar flare gamma-ray lines, on a survey of hard X-ray binary sources and their identification, on the origin of the "diffuse" galactic ridge emission, and on gamma-ray bursts. Whereas line measurements generally require deep exposures of several million seconds (1 month and more), results on compact objects can be obtained much easier – in most cases they require exposures of only one or a few days.

Keywords: gamma-ray astronomy, gamma-ray sources, gamma-ray line spectroscopy

1. INTRODUCTION

The International Gamma-Ray Astrophysics Laboratory (INTEGRAL) of ESA is on its way to become a major milestone in hard X-ray and low energy gamma-ray astronomy after the successful missions of SIGMA on GRANAT and the Compton Gamma-Ray Observatory. INTEGRAL is mainly devoted to high resolution spectroscopy and fine source imaging in the energy range 15 keV and 10 MeV. With its high resolution spectroscopy capabilities it fills a gap which was neither covered by SIGMA nor CGRO. The excellent imaging performance of INTEGRAL is comparable to that of SIGMA, but at a sensitivity level which is a factor of about five to ten higher.

INTEGRAL was launched on October 17, 2002. A Russian Proton rocket brought the spacecraft into an excentric 72 hour orbit of 153.000 km apogee and 9.000 km perigee (51.6° inclination). An extension of the mission life time beyond the nominal 2 years until 2008 is already granted. INTEGRAL is operated as an observatory: most of the observation time is available to the scientific community, a core-program (35 % in the first years, 30 % in the second year, and 25 % thereafter) is reserved for ESA's INTEGRAL Science Working Team.

After a successful performance and verification phase in November/December 2002, the observational program started thereafter by executing open-time proposals and guaranteed core-time observations. A wealth of interesting results has been obtained during the first 18 months of the mission, the highlights of which will be described below.

2. THE SCIENTIFIC INSTRUMENTS OF INTEGRAL

INTEGRAL carries four instruments: the two main instruments SPI and IBIS, and two monitors JEM-X and OMC (Fig. 1). The spectrometer SPI (20 keV to 8 MeV) is 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, its energy resolution at 1 MeV is 2.5 keV FWHM (1). The imager IBIS (15 keV to 10 MeV) has an excellent angular resolution of 12 arcmin within its fully coded field-of-view of 9° FWHM, its energy resolution is modest (10 % FWHM at 1 MeV) (2). The two monitor instruments allow parallel monitoring of the gamma-ray sources in the adjacent X-ray band and at optical wavelengths.

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JEM-X (3-35 keV) has an angular resolution of 3 arcmin in its 4.8° FWHM field-of-view (3) and the optical camera OMC (500-600 nm) has a pixel resolution of 16.6 arcsec within its 5°x5° field-of-view (4).

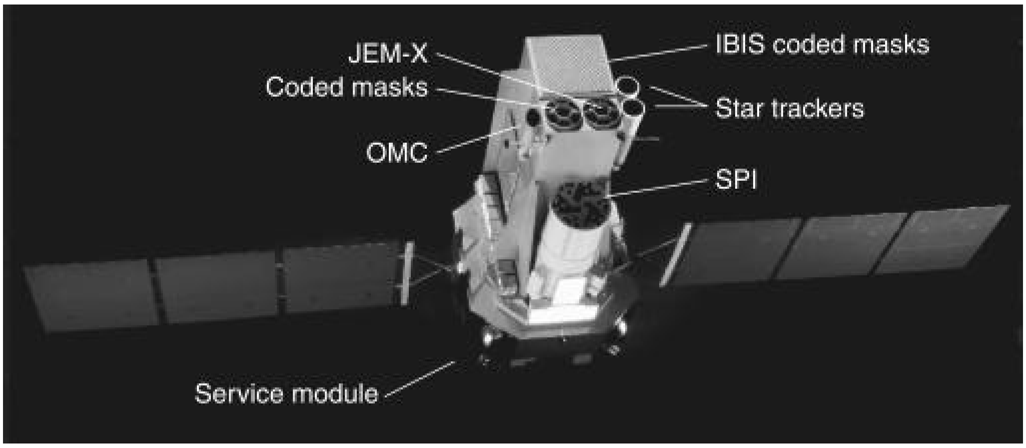

Fig. 1. Schematic View of INTEGRAL

SPI, IBIS, and JEM-X are all three based on the coded aperture imaging technique. SPI uses cooled germanium detectors, IBIS uses CdTe-detectors for the low-energy range (called ISGRI), and CSI-detectors for the high energy range (called PICSIT), and JEM-X uses microstrip Xenon gas detectors. OMC consists of a passively cooled CCD in the focal plane of a 50 mm lens. Cosmic gamma-ray line measurements with SPI general require deep exposures of several million seconds (1 month or more), results on continuum emission below 1 MeV from gamma-ray sources with IBIS and SPI can be obtained in most cases on a much shorter time scale of order 1 day or a few days. The SPI narrow line sensitivity at the 3s confidence level is illustrated in Fig. 2, and the 3s continuum sensitivities of IBIS and SPI are shown in Fig. 3, in both cases for an observation time of 10^6 seconds.

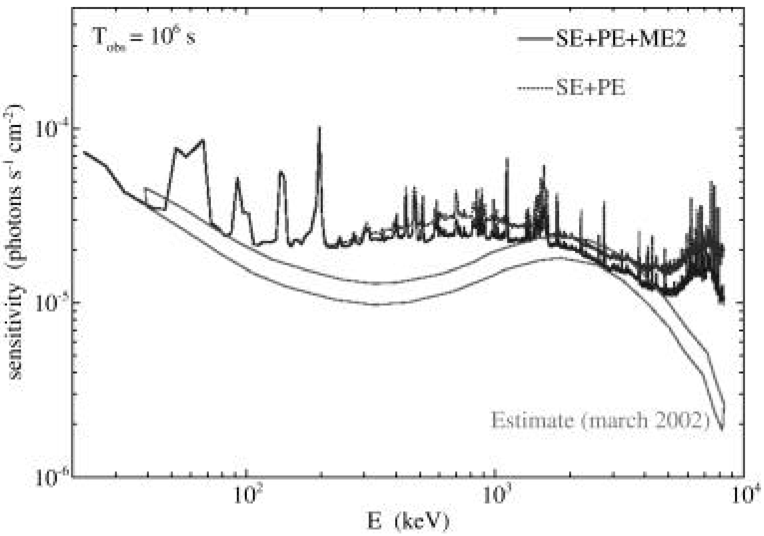

Fig. 2. Actually measured 3s narrow line sensitivity of SPI for 10^6 sec observation time (1). Between ~ 100 keV and 1.5 MeV pulse shape discrimination did not fulfil the pre-launch expectations (1). The term “narrow” is defined to be identical to the energy resolution of the instrument. For broadened gamma-ray lines, the sensitivity is degraded.

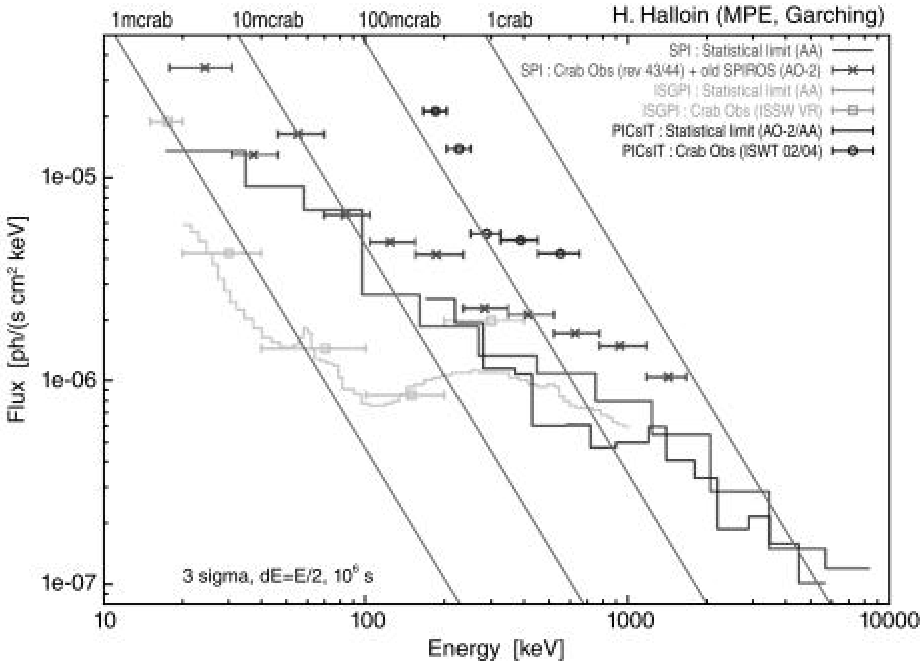

Fig. 3. 3s continuum sensitivities of IBIS (for ISGRI and PICSIT separately) and SPI in energy bands ?E = E/2 for 10^6 sec observation time. The sensitivity curves are shown for 2 cases: first, assuming only statistical uncertainties of the background; second, by adding the impact of systematic background uncertainties and the impact of imaging methods. The Crab-spectrum and fractions of the Crab-spectrum are shown to guide the eyes. Compiled by (5).

3. SELECTED HIGHLIGHT RESULTS FROM INTEGRAL

The observations of INTEGRAL so far mainly concentrated towards the Galactic plane, and especially the inner Galaxy. In Fig. 4 the exposure map for the IBIS field-of-view is shown as expected in February, 2005 (from (6)). The deepest exposures are towards the Galactic center, the central radian of the Galaxy, and the Cygnus-, Cas-A-, Vela-, Crab-, and LMC-regions.

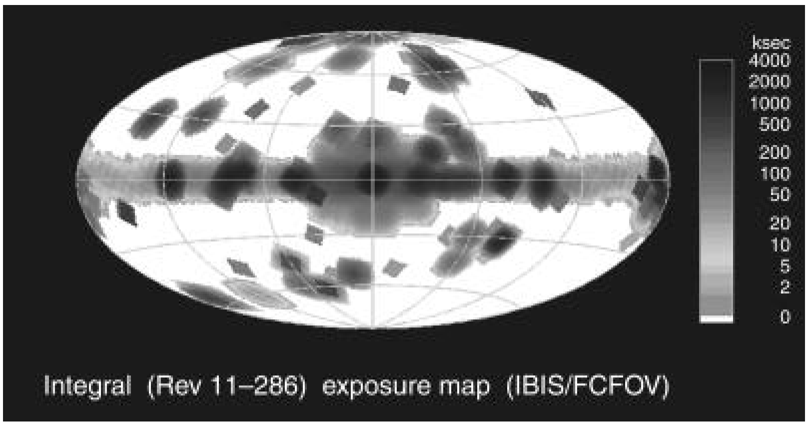

Fig. 4. Expected exposure map for the fully coded IBIS field-of-view from November 2002 to February 2005.

Highlights from the first 18 months of the mission are results on nucleosynthesis – and solar flare gamma-ray lines, on a survey of compact hard X-ray binary sources and attempts of their identification, on the origin of the “diffuse” Galactic ridge emission, and on gamma-ray bursts. These topics will now be described in more detail.

3.1 INTEGRAL Gamma-Ray Line Measurements

Gamma-ray line spectroscopy is the main research field of SPI. 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 0857-4622, from which COMPTEL found evidence for 1.157 MeV emission from radioactive ^{44}Ti, any 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 (847 keV, 1.238 MeV) and ^{57}Co (122 keV) gamma-ray line emission, and any nearby (typically <1 kpc) classical nova to search for the 478 keV and 1.275 MeV lines from radioactive ^{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. Other interesting objects may be sources of sporadic electron-positron annihilation emission (like Novae Muscae and 1 E 1740.7-2942) which are expected to be discovered during the bi-weekly Galactic plane scans of INTEGRAL. Also the Sun is an intense gamma-ray line emitter during strong solar flares.

SPI has measured the profiles of the 1.809 MeV line from radioactives ^{26}Al during deep exposures of the Galactic central radian and the Cyg-region ($73^{\circ} < l < 93^{\circ}$, $|b| < 7^{\circ}$) (see Fig. 5). Both these regions are known from the COMPTEL all-sky survey to be bright regions of 1.809 MeV line emission. Still, the SPI-measurements are difficult, since the signal-to-background-ration is only in the ~ %-range.

The line fluxes from both regions are $(4 \pm 1) \times 10^{-4}$ ph cm^{-2} sec^{-1}, and $(7.3 \pm 0.9) \times 10^{-5}$ ph cm^{-2} sec^{-1}, respectively, and the intrinsic line widths exclude previously reported line broadenings of >500 km sec^{-1} (9). The statistics from these and other 1.809 MeV emitting regions will be improved over the years, in order to be able to better constrain the intrinsic line width, thus providing valuable information about the ejecta dynamics.

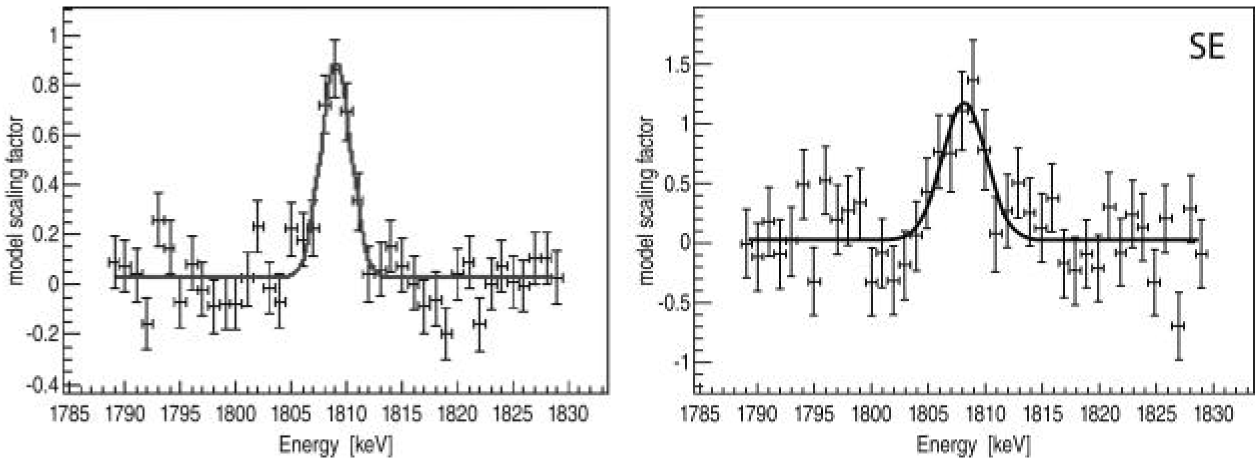

Fig. 5. SPI has measured the 1.809 MeV line profile from 2 regions of the COMPTEL all-sky map: from the inner central radian (left side), and from the Cygnus-region (right side) (from (7) and (8)).

The electron-positron annihilation line at 511 keV has been measured by SPI with high precision (significance ~ 20s), (10). The emission is only visible in the bulge region around the galactic center of 8 ($^{+3}/_{-2}$) degrees diameter. The measured line flux of $(0{,}96^{+0.21}/_{-0.14}) \times 10^{-3}$ ph cm^{-2} sec^{-1} implies an annihilation rate of $(1\text{-}2) \times 10^{43}$ sec^{-1}. The intrinsic line width is $(2.76^{+0.30}/_{-0.33})$ keV (FWHM); it is determined by the temperature, the density and the ionisation degree of the medium (Fig. 6). In order to detect 511 keV line emission from the Galactic disk in the inner radian (which must exist at least from e^+- decay of ^{26}Al at the level of ~ 2 × 10^{-4} ph cm^{-2} sec^{-1} rad^{-1}), deeper exposures of SPI are still needed. The origin of the positrons in the bulge region is a mystery. The yield from $ß^+$-decay of radioactive isotopes produced in supernovae and novae seems insufficient for an explanation. Recently, it has been suggested that the annihilation of dark matter particles in the Galactic halo can produce the positrons observed in the bulge (11)

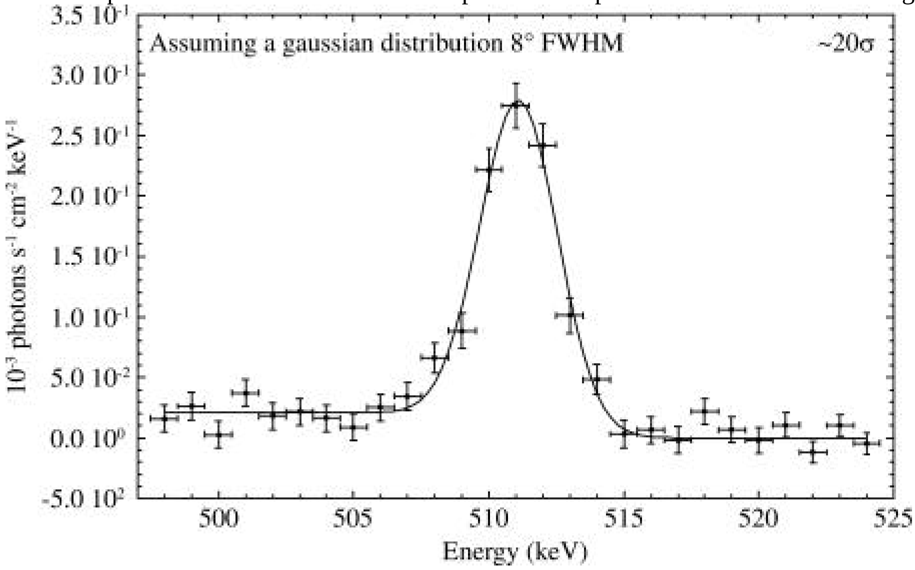

Fig. 6. Spectrum of the 511 keV line measured by SPI from the Galactic Bulge region (10)

The 1.173 and 1.332 MeV lines from the radioactive ^{60}Fe-decay chain are the weakest expected narrow gamma-ray lines from interstellar space (the flux of each of the 2 lines is expected to be 8 % of the flux in the 1.809 MeV line (12)). At present SPI has not yet succeeded in a significant detection of the ^{60}Fe-lines. Systematic uncertainties limit the sensitivity for both lines at about ~ 10^{-4} ph cm^{-2} sec^{-1} rad^{-1} (13). Once the systematic uncertainties have been reduced below the statistical uncertainty of the data (which at present are at a level of ~ 2.5x10^{-5} ph cm^{-2} sec^{-1} rad^{-1}), we can expect either the detection of both lines or the most stringent upper flux-limits. Since ^{60}Fe is supposed to be primarily produced in core-collapse supernovae, the detection of ^{60}Fe line emission and a resulting map in the lines would provide a tracer for Galactic supernova activity and a comparison of the ^{20}Al and ^{60}Fe-maps would allow to identify the supernova contribution to the ^{20}Al-map.

Nucleosynthesis gamma-ray lines from individual sources, like supernovae (^{56}Co- and ^{57}Co-decay lines) or novae (^{7}Be- and ^{22}Na-decay lines, and $ß^+$-decay from ^{13}N and ^{18}F) are expected to be broadened due to the expansion velocities of the ejected material. The occurrence of a nearby supernova (<6 Mpc), or a nearby nova (<1 kpc) is eagerly expected.

Also the 67,9 keV, 78,4 keV, and 1.157 MeV lines from radioactive ^{44}Ti (decay-time ~ 90 years) produced in individual supernova should be broadened. The SPI- and also IBIS-sensitivities (for the 67,9 keV and 78,4 keV lines) are not yet sufficient to confirm the COMPTEL (14) and Beppo-SAX (15) detections from Cas-A, as well as the possible COMPTEL detection from Vela Junior (RX 0852-4622), (16), (17). For upper limits from INTEGRAL to the ^{44}Ti-line fluxes see ref. (18). Also, a search for unknown supernova remnants in the central radian of the Galaxy by the ^{44}Ti-line emission so far remained unsuccessful: IBIS lowered the 1σ flux limit of COMPTEL (19) by ~ 50 % to 5.5 × 10^{-6} ph cm^{-2} sec^{-1} (20).

Instead, INTEGRAL detected the first broadened gamma-ray line emission from the Sun during the strong solar flare on October 28, 2003 (21). Though INTEGRAL is never oriented towards the Sun, SPI is able to detect solar flare gamma-ray lines in its germanium detector array, if the gamma-rays pass through the anticoincidence shield without interactions (the transparency of the shield is of order 10 to 15 % above 1 MeV). Apart from continuum emission, a number of gamma-ray lines (especially at 511 keV, 2.22 MeV, 4.43 MeV, and 6.13 MeV) has been observed from this flare by SPI (21)

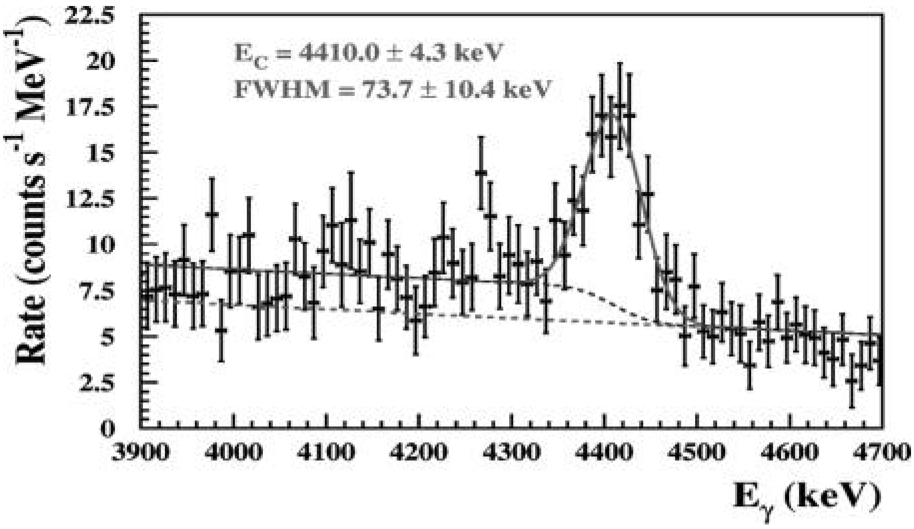

Fig. 7. Line profile of the 4.43 MeV line observed by SPI during the October 28, 2003 solar flare (21).

The onset of the continuum emission and the onset of the various line emissions all occur at different times, indicating that acceleration times are different for electrons and ions. As an example, Fig. 7 shows the nuclear interaction line from excited Carbon and Oxygen nuclei at 4.43 MeV. The line is redshifted by 0.63 % towards the peak energy of 4.410 MeV, and the line profile shows a width of 1.67 % FWHM.

3.2 INTEGRAL Survey of Hard X-Ray Sources

The study of hard X-ray sources is the prime objective of IBIS (especially ISGRI). From the combination of deep exposures of the inner Galactic central radian and the regular bi-weekly Galactic plane scans in 2003, a first IBIS source catalogue has been produced for the inner central radian, which contains 123 sources detected down to a limiting sensitivity of ~ 1 mCrab in the energy range 20-100 keV (22). Each source is located to an accuracy between 1' and 3'. Previous surveys in this energy range had limiting sensitivities of 14 mCrab (HEAO 1 A4 (23)), and ~ 30 mCrab (SIGMA (24)). The IBIS Catalogue contains (among others) 23 HMXBs, 53 LMXBs, five AGNs, and a further 28 sources not associated with any one type object. The sources belong to all possible classes: most of them are accreting Galactic binaries with either a neutron star or black hole. A few are pulsars (with and without SNRs). In the same part of the sky, SPI so far has resolved 37 sources between 20 to 66 keV, and 17 sources between 66 to 163 keV (25).

Binaries studied by INTEGRAL are (among others), the BH-system Cyg X-1 (26,27), the periodic HMXB microquasar Cyg X-3 (28), the periodic binary X-ray pulsar EXO 2030+375 (29), the flaring X-ray binary pulsar Vela X-1 with cyclotron line emission (30), and the microquasars GRS 1915+105 (31) and SS433 (32) for both of which multiwavelength observations have been carried out.

As an example Fig. 8 shows the energy spectrum of the black-hole system Cyg X-1 measured by SPI during 1 week of the INTEGRAL verification phase in November/December 2002 (26) in comparison with previous 1 keV to 10 MeV CGRO and Beppo-SAX observations (33) in two different states of Cyg X-1, which are characterized by its intensity in the keV-range. At the time of the INTEGRAL observations, Cyg X-1 was close to its "low" keV state. The high keV-intensity represents a state of a high accretion rate, and the low keV-intensity one of low accretion rate. The high intensity state is relatively rare (~ 10 % of the time). There is a direct correlation between the keV and MeV-flux, and anti-correlation between the keV- and the 100 keV-flux. Different accretion rates obviously trigger different emission geometries and mechanisms. Not only the intensity, but also the overall spectral shape is influenced by the accretion rate. The overall spectra can be interpreted as superposition of black body radiation (at keV-energies), Compton scattering of thermal and non-thermal electrons, and Compton reflection radiation. The origin of the non-thermal electrons (required above ~ 1 MeV) is not well understood. The 1 week INTEGRAL exposure was not sufficient to detect the very weak emission above 1 MeV (COMPTEL needed 2 months of exposure to detect it).

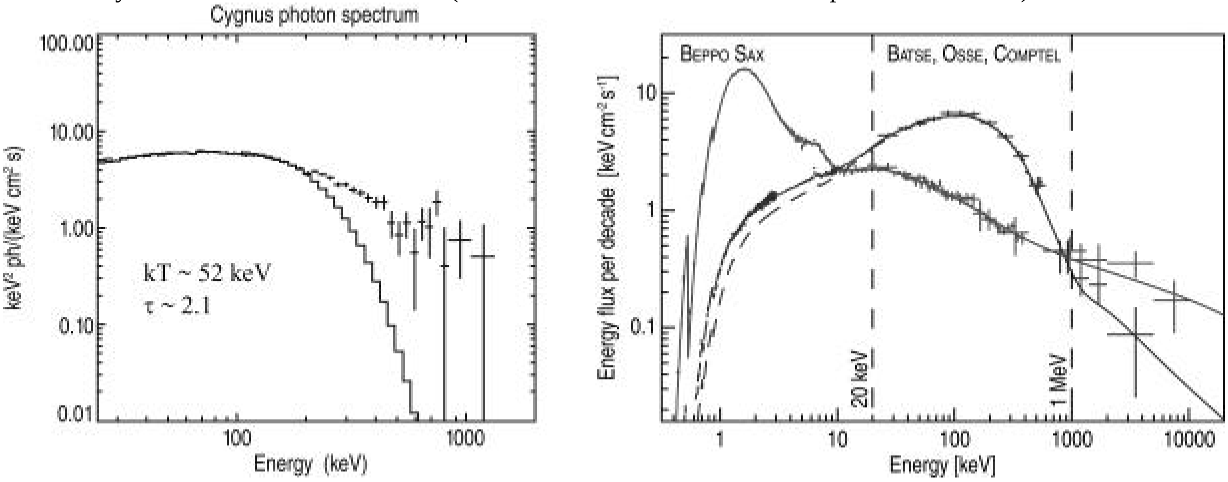

Fig. 8. Spectrum of Cyg X-1 measured by SPI-INTEGRAL (left side) during its low keV-state in comparison with the classical "2-state" spectra as measured by GRO and Beppo-SAX (right side).

A surprise was the unexpected INTEGRAL discovery of a new type of highly absorbed X-ray binary sources which had so far escaped previous detection with other instruments. The very first of these sources – named IGR J6318-4848 – was detected in the IBIS/ISGRI images of the first Galactic Plane Scan performed on the Norma arm region of the Galaxy on January 29, 2003. An XMM TOO-observation was performed on February 10, 2003. A single X-ray source was found in the ISGRI error box, and an infrared counterpart was identified on February 19, 2003. (34, 35). From spectroscopic observations, the system is likely a HMXB. The source features recurrent flares and the flares last typically 1 hour. During the flares the source is typically 10-times brighter than on average.

Fig. 9 shows the spectrum observed by XMM and IBIS/ISGRI between 3 keV and 80 keV. The X-ray spectrum around 5 keV is characterized by strong photoelectric absorption with an associated Fe absorption edge at 7.1 keV and several fluorescence lines. The derived absorbing column density is of order 2×10^{24} cm^{-2}. It is supposed that the absorbing gas resides in the binary system. It is probably related to the accretion flow or stellar wind from the high mass stellar companion.

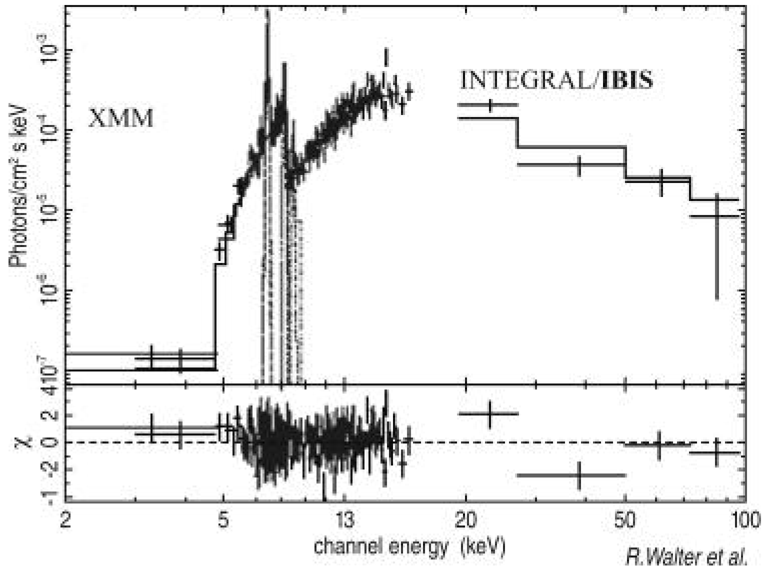

Fig. 9. The spectrum of the highly absorbed source IGR J6318-4848 as measured by XMM and IBIS/ISGRI (34).

In the meantime INTEGRAL has discovered 8 new sources in the Norma arm tangent region of the Galaxy. The Norma arm is the region of the highest OB-star formation rate in the Galaxy. It is also – apart from the Galactic Center region – the region of the plane with the highest density of sources detected by INTEGRAL. It is, therefore, likely that several of the new INTEGRAL sources are HMXBs. For half of them, high absorption has been observed in X-rays by Chandra, XMM or ASCA (35). Strongly absorbed sources, not detected in previous surveys, could significantly contribute to the Galactic hard X-ray background (see below!).

The Galactic center is a prime target for INTEGRAL, and deep exposures have been made towards this region. Summed IBIS/ISGRI images have been constructed in the energy ranges 20-40 and 40-100 keV leading to the discovery of a source (IGR J17456-2901) which coincides with the Galactic Nucleus SgrA* to within 0.9 arcmin (36, 37). Although this source cannot unambiguously be identified with SgrA*, this is the first report of significant hard X-ray emission from the inner 10 arcmin of the Galaxy, and a contribution from the super-massive black-hole in the center of our Galaxy cannot be excluded. The source is visible up to 100 keV with a 20-200 keV luminosity of $(2.89 \pm 0.41) \times 10^{35}$ erg sec^{-1}, if placed at a distance of 8 kpc.

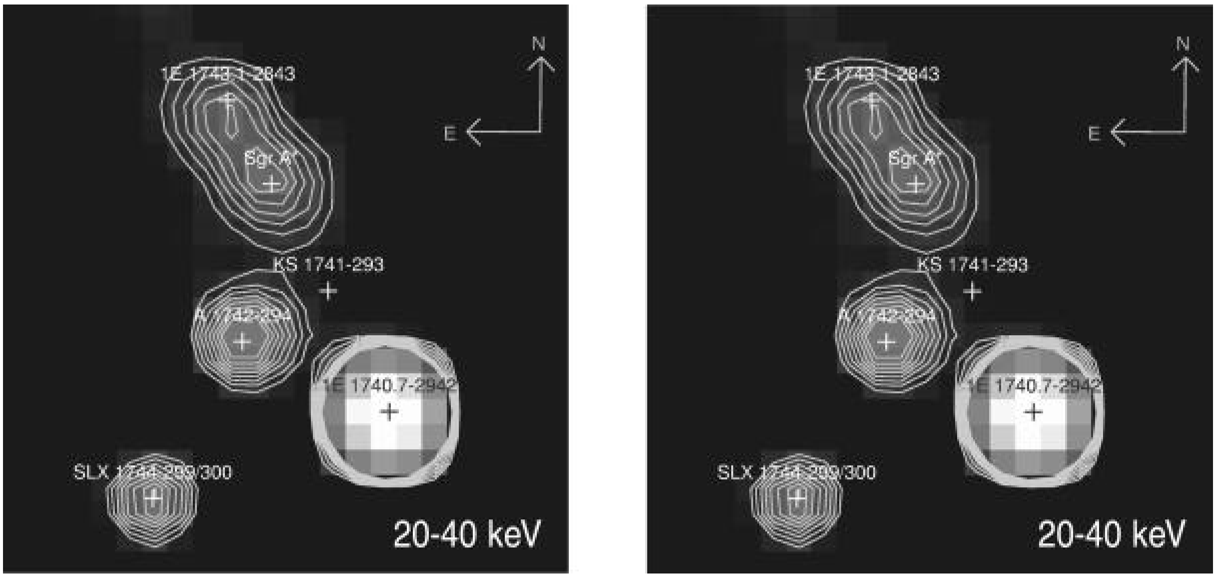

Fig. 10. IBIS/ISGRI $2^{\circ} \times 2^{\circ}$ image around the Galactic center, left side: 1.2 Msec exposure in February-October, 2003, right side: 1 Msec exposure in September 2003 (from (37)). The new source whose contour lines are those around SgrA* is displaced by only 52'' (left side), and 40'' (right side) from SgrA* (at a position uncertainty of 1').

3.3 Diffuse Galactic Continuum Emission

The origin of the diffuse X- and gamma-ray background in the inner ridge of the Galaxy is of interest since its discovery in the late sixties / early seventies. More recent observations at soft and hard X-ray energies are from ASCA, Ginga, RXTE, SIGMA, Chandra and XMM-Newton, the soft and medium gamma-ray band up to 30 MeV has been studied by OSSE and COMPTEL, and above 100 MeV extensive measurements exist from EGRET. Crucial for measuring the diffuse emission is its separation from the contribution of point sources. Up to ~ 10 keV 80 % of the ridge emission is probably diffuse for small sky regions of order 1°, which do not contain bright sources (38). At high X-ray energies, the lack of sensitive instruments with sufficient imaging resolution was the main problem to determine the truly diffuse component. From the combination of SIGMA and OSSE-observations it was concluded that about 50 % of the total inner ridge emission between say 50 to 500 keV was due to sources. The explanation of the remaining diffuse component was and still is a challenge. While the physical process (e^+-e^--annihilation) producing positronium continuum between ~ 200 keV to 500 keV is clear, for the remaining continuum it is not, although non-thermal electron bremsstrahlung is most likely. The implied photon luminosity in the continuum of a few 10^{38} erg sec^{-1} is an energetic problem (39, 40).

The high imaging resolution of IBIS/ISGRI combined with the unprecedented sensitivity of ISGRI and SPI has now allowed a clear separation between sources and diffuse emission: Subtracting the contribution of 91 sources detected by ISGRI (42), a truly diffuse component remains above 20 keV which is approximately 10 to 15 % of the total ridge emission in the inner central radian.

Fig. 11 shows both, the "diffuse" (left side) and the "total source" spectrum (right side) as derived by SPI from the inner central radian (from (41)). The diffuse SPI spectrum is compared with RXTE-results below 20 keV, and with COMPTEL-results (1 to 30 MeV). A three-component-fit is applied to the diffuse spectrum consisting of an exponentially cut-off power law, a high energy continuum power law, and the positronium component. The extrapolation of the power-law component into the COMPTEL-range above 1 MeV suggests that only part of the total measured COMPTEL flux is of diffuse origin. An independent analysis of ISGRI-data in the 20 to 200 keV band led to the same diffuse fluxes in the central ridge (41, 42, 43). These SPI and ISGRI results have an impact on the shape and the intensity of the really diffuse spectrum between 20 keV and 30 MeV, which will require a re-discussion of its origin.

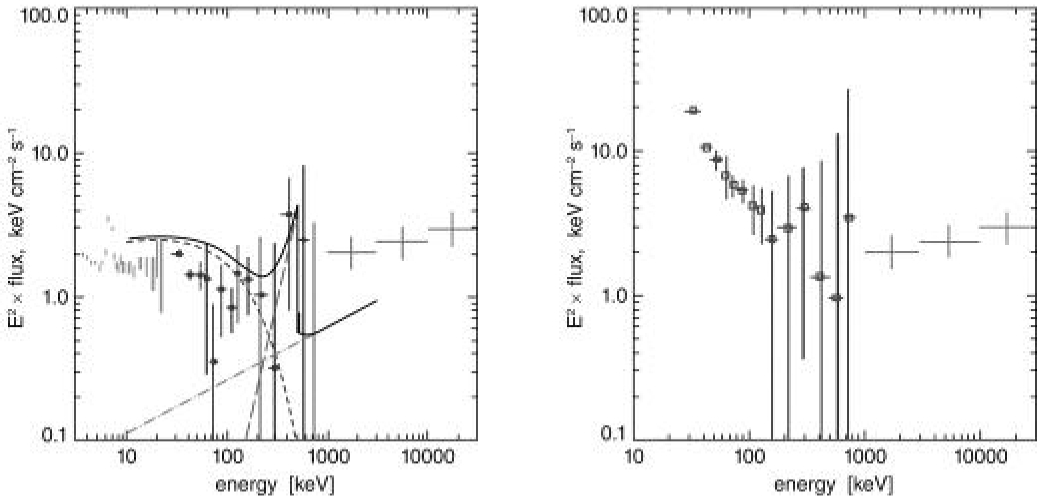

Fig. 11. Diffuse continuum (left side) and summed source spectrum (right side) from SPI-data of the Galactic Central radian. Above 1 MeV the total COMPTEL emission in the central radian is shown for comparison in both diagrams. The diffuse spectrum below 20 keV is from RXTE (from (41)).

3.4 Gamma-Ray Burst Astronomy with INTEGRAL

Although gamma-ray burst astronomy is only a secondary objective of INTEGRAL, the first part of the mission has demonstrated that INTEGRAL can provide rapid information on the onset of a burst, in order to initiate observations of any afterglow, or a counterpart search, at other wavelength. For this purpose an automatic "INTEGRAL Burst Alert System" (IBAS) has been developed, which provides arcmin locations within a few tens of seconds after the gamma-ray burst event (44).

At present, no other spacecraft in orbit, is faster in this respect, than INTEGRAL. Up to April 30, 2004, a total of 12 gamma-ray bursts has been observed in the fields-of-view of SPI (45) and IBIS (46), and their locations, energy spectra and time profiles have been measured. For half of them, afterglow emission was observed in the radio, optical and/or X-ray range.

In addition, the nearly omni-directionally sensitive anti-coincidence system of SPI is operated as a very sensitive gamma-ray burst detector, which provides light curves with 50 msec time-resolution. The precise timing combined with measurements from other missions in the Interplanetary Network provide accurate burst positions (47, 48). During the first 15 months of the mission 256 bursts were triggered by the SPI anti-coincidence, 111 of these were confirmed by triggers in other satellites of the Interplanetary Network.

4. CONCLUSIONS

The bulk of results obtained so far from INTEGRAL are from IBIS/ISGRI and from SPI. Both these instruments are performing extremely well.

Most of the INTEGRAL-results of the first 1 ½ year are on X-ray binaries. This is because significant results on a specific source can be obtained within relatively short observation times of typically 1 day. The first INTEGRAL source surveys with more than 100 objects in the inner Galaxy region have revised our knowledge about the diffuse continuum spectrum of the Galactic ridge at hard X-ray / soft gamma-ray energies, and the discovery of highly absorbed X-ray binaries as a new class of X-ray sources came as a surprise. Here, the combined measurements of XMM and INTEGRAL turned out to be extremely fruitful.

In the field of gamma-ray line astronomy SPI has demonstrated its excellent capability to do high resolution spectroscopy. Considering the low signal-to-background ratios, the first impressive results on line profile measurements of the 511 keV and 1.809 MeV lines came earlier than expected. The measurements of gamma-ray lines from the October 28, 2003 solar flare is another demonstration of SPI's excellent performance.

In the field of gamma-ray burst astronomy, INTEGRAL has turned out to be the fastest trigger provider of all spacecrafts presently in orbit.

Based on these early results, we can be confident that INTEGRAL will fulfil its expectations on science, with some loss in sensitivity, which will be partly compensated by the approved extension of the mission till 2008.

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