Highlights from *Integral*: Two Years in Orbit

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The *International Gamma-Ray Astrophysics Laboratory Integral* (Winkler *et al*. 2003) was launched on 17 October 2002 at 0441 UTC from Baikonur Cosmodrome (Kazakhstan). The four-stage Proton launch vehicle injected the spacecraft into its 72-hour orbit with utmost precision. The initial orbital parameters are perigee height: 9000 km; apogee height: 154 000 km; inclination: 52.2º. After a nominal commissioning phase, science observations began on 30 December 2002. *Integral* carries two main gamma-ray instruments: the spectrometer – SPI, optimized for the high-resolution gamma-ray line spectroscopy, consists of 19 cooled germanium detectors operating in the 20 keV – 8 MeV range. The angular resolution within the 16º Full-Width Half-Maximum (FWHM) coded mask is 2.5º FWHM and its energy resolution at 1 MeV is 2.5 keV FWHM. The imager – IBIS, optimized for high-angular resolution imaging, operates in the 15 keV – 10 MeV band with 9×9º FOV (FWHM) and excellent angular resolution of 12 arcmin (FWHM).

The energy resolution is 10% at 1 MeV. Two monitors (JEM X in the 3 – 35 keV X-ray band, and OMC in optical Johnson V-band) complement the payload.

The science objectives for *Integral* are mainly driven by high-resolution spectroscopy with fine point source imaging of high-energy sources. With its energy resolution capabilities, *Integral* fills a gap left by the two previous gamma-ray missions *Granat*/*SIGMA* and *CGRO*. The angular resolution of IBIS is comparable to that of SIGMA, but with a much-improved sensitivity. SPI, IBIS and JEM-X use the common principle of coded aperture mask imaging techniques.

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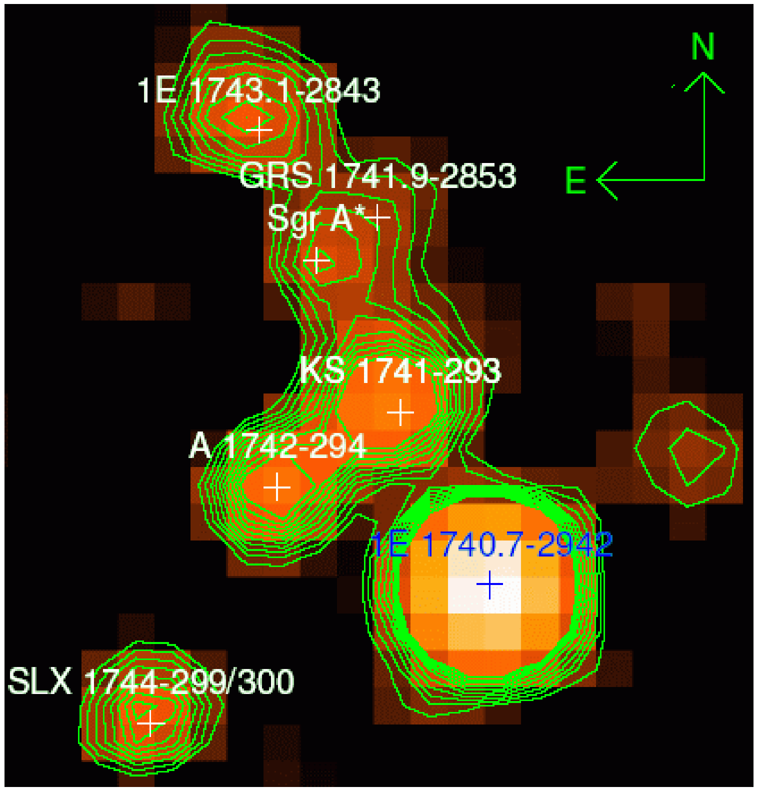

Figure 1. This image shows the centre of our Galaxy in a 2º by 2º field as observed with the IBIS/ISGRI instrument onboard *Integral* in the energy range from 20 to 40 keV. Clearly visible is a new source coincident with the galactic nucleus Sgr A* to within 0.9 arcminutes. This source is visible up to about 100 keV. [G. Belanger (CEA-Saclay, France) *et al*. 2004].

What follows is a selection of scientific highlights, achieved during the first two years of science operations. The selection is a subjective choice by the author and does not cover all results[1] obtained so far. Clearly, the Galactic Centre is one of the prime targets for *Integral*: it harbours many compact objects, sources of diffuse emission and, last-but-not-least, a super-massive black hole, which is surprisingly weak at high energies. The centre of our Galaxy was observed with the IBIS/ISGRI instrument onboard *Integral* in the energy range above 20 keV (Belanger *et al*. 2004). A new source coincident to within 0.9 arc minutes with the Galactic nucleus SgrA*, believed to be the counterpart of the super-massive black hole, has been detected at energies up to about 100 keV. The luminosity (20 – 120 keV) is only 5×10^{35} erg s^{-1} (4.3 milliCrab). The source cannot be explained by simple extrapolation of the point/diffuse X-ray emission as measured by *XMM-Newton* and *Chandra* (see *SRT 162*, p. 5 *et seq* and p.19 *et seq*). Also it is not associated with other high-energy (> 10 keV) sources or with non-thermal structures (e.g., radio arcs) of that region (see Figure 1).

This new *Integral* source is the first report of persistent hard X-ray emission from the central 10 arcminutes of our home Galaxy. Although other sources within this region might contribute, there is a distinct possibility that we are seeing hard X-ray emission from the super-massive black hole at the centre of our Galaxy for the first time.

Is it possible that Sgr A* was much brighter in the past? This hypothesis has been successfully tested using scattering of X-rays

[1] See http://integral.esac.esa.int/Publications

by molecular clouds. *Integral* observations of the molecular cloud Sgr B2 indeed show, for the first time, this source at energies above 20 keV (Revnivtsev *et al*. 2004). The observed hard X-ray continuum, a hard power law of index 1.8, together with a cut-off > 100 keV due to recoil of photons and a strong fluorescence line at 6.4 keV as observed by *ASCA*, were used to model the input spectrum of Sgr A* which is then similar to a low-luminosity Active Galactic Nucleus (AGN). It has been concluded that, about 350 years ago (corresponding to the light travel time between Sgr A* and Sgr B2), Sgr A* was 4 orders of magnitude more luminous than it is today. This conclusion is supported by the observation that the 6.4 keV line remained stable over ~ 10 years, hence excluding any transient X-ray binary close to Sgr B2 as the illuminating source. The Galactic Centre is also a region where the annihilation of electrons with their anti-matter equivalents – positrons, takes place. This annihilation produces a gamma-ray line at 511 keV through direct annihilation, and continuum emission at lower energies due to the formation and decay of positronium. The sources producing positrons are a matter of hot debate. *Integral*'s SPI instrument provided an all-sky map of the 511 keV emission, showing that this emission, so far, is only seen towards the centre of our Galaxy (Knoedlseder *et al*. 2005). The distribution is almost symmetrical (FWHM = 8º) centred on the Galactic Centre with a very weak disk component (see Figure 2). The luminosity ratio between bulge and

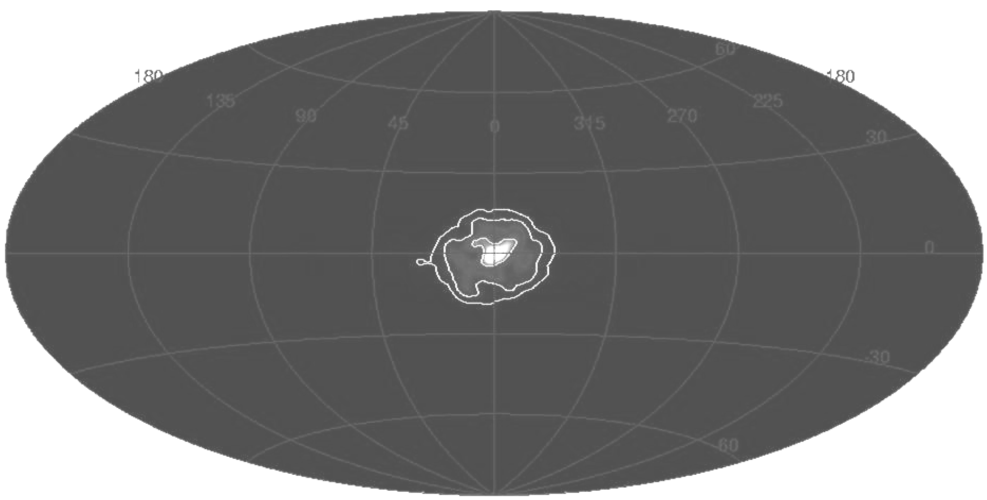

Figure 2. The SPI instrument onboard *Integral* has performed a search for 511 keV emission (resulting from positron-electron annihilation) all over the sky. The figure represents the results of this search: the all-sky map in Galactic coordinates shows that 511 keV emission is only seen towards the centre of our Galaxy. [J. Knoedlseder (CESR Toulouse) *et al*. 2005].

disk – derived from the annihilation rates – is in the range between 3 and 9 and imposes severe constraints on the principal sources of positrons. The SPI data are equally compatible with Galactic bulge or halo distributions, the combination of a bulge and a disk component, or a combination of a number of point sources. Such distributions are to be expected if positrons originate either from low-mass X-ray binaries, novae, Type Ia supernovae or, possibly, light dark matter. The earlier *CGRO*-OSSE observations of a high latitude enhancement in the 511 keV distribution, tentatively attributed to a (local?) 'fountain' of antimatter, could not be confirmed.

The deep observations of the Galactic Centre region also provided a high-resolution high quality spectrum around the 511 keV line (see Figure 3) with unprecedented stringent constraints on the physical environment of the annihilation region in the interstellar medium. The observed line is unshifted, while the line parameters on energy, E = 510.954 ± 0.075 keV, and line width, FWHM = 2.37 ± 0.25 keV, are compatible with annihilation in a warm (8000K), mildly ionized single-phase interstellar medium (ISM) (Churazov *et al.* 2005).

A key puzzle solved by *Integral* concerns the contribution of discrete point sources to the Galactic diffuse soft gamma-ray background. Before *Integral*, it was difficult to separate point sources and the diffuse component at hard X-ray energies. Previous observations by SIGMA and *CGRO*-OSSE showed that 50% of the 50 – 500 keV emission was from point sources. It was then difficult to assign the remaining 50% to soft gamma-ray diffuse emission processes, to inverse Compton scattering or Bremsstrahlung: the inverse Com-

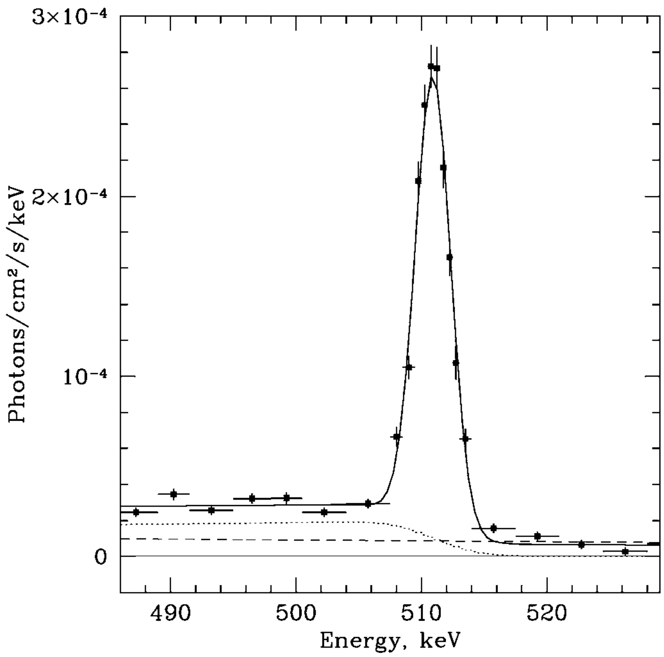

Figure 3. The electron-positron annihilation spectrum observed by *Integral*–SPI during the deep exposure of the Galactic Centre region. The line energy, E = 510.954 ± 0.075 keV, is consistent with the unshifted annihilation line. The width of the annihilation line is FWHM = 2.37 ± 0.25 keV, while the strength of the ortho-positronium continuum (dotted line) suggests that the dominant fraction of positrons (94 ± 6 %) form positronium before annihilation. Compared to previous missions, these deep *Integral* observations provide the most stringent constraints on the line energy and width. [E. Churazov (IKI Moscow & MPA Garching) *et al.* 2005.]

pton scattering of GeV cosmic ray electrons would, due to the large number of required electrons, produce radio-synchrotron emission at a much higher level than observed. Bremsstrahlung of ~100s keV electrons in the ISM requires ~ 10^{43} erg s^{-1}, corresponding to the total cosmic-ray luminosity of the Galaxy, which should affect the ISM ionization equilibrium and dissociation of ISM molecules.

With its superior ability to see faint details, *Integral* showed, for the first time, that individual point sources comprise most of the foggy gamma-ray radiation seen by previous observatories. The brightest 91 objects identified by *Integral* as individual sources almost entirely account for the diffuse emission observed by previous instruments and leaves only a minor role for the processes described above (Lebrun *et al*. 2004).

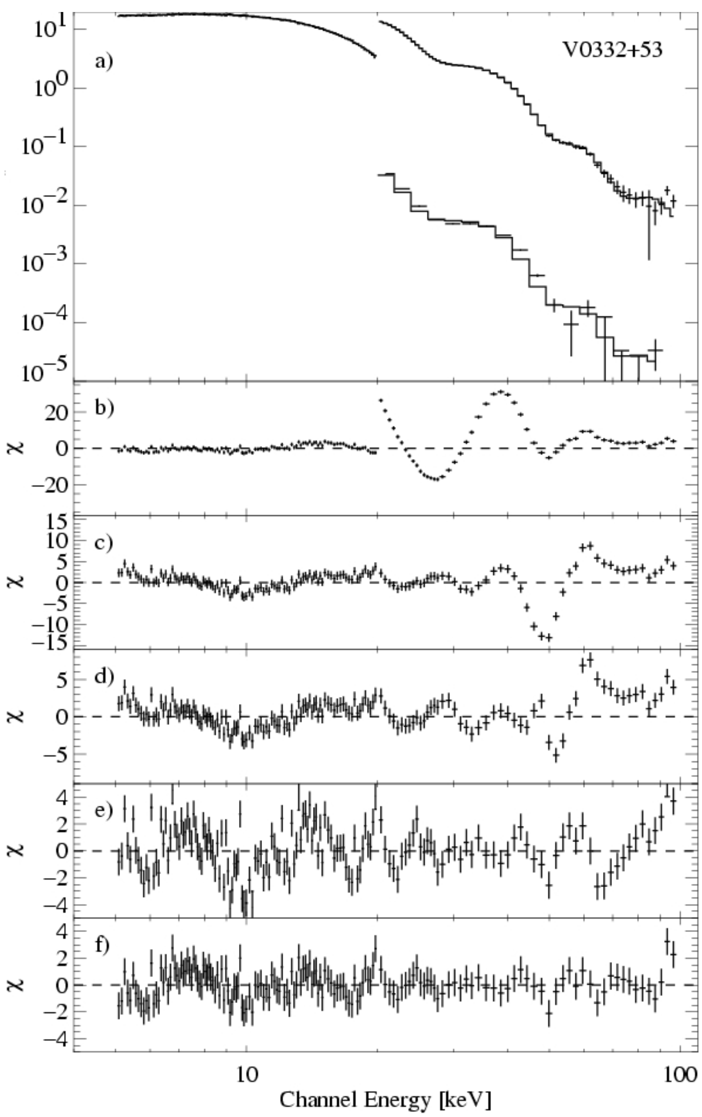

Figure 4. The high mass X-ray binary V0332+53 was observed by *Integral* during an outburst between 7 and 10 January 2005. Panel a) shows the raw spectrum of JEM-X (upper left), IBIS (upper right) and SPI (lower right). Panel b) shows the residuals to the best-fitting continuum model. Panels c) to f) show the residuals with respect to models in which an extra line has been added at a time at c) 26.6 keV, d) 47.1 keV, e) 30.8 keV, and f) 71.7 keV, respectively, to fit the observed residual. [Kreykenbohm *et al*. 2005].

A surprise was the unexpected discovery by *Integral* of a new type of highly absorbed X-ray binary sources that hitherto had escaped detection by other missions. These objects can be characterized by hard spectra at high energies and strong photoelectric absorption, most likely caused by the stellar wind and accreting material of the companion star below a few keV. From spectroscopic observations, these objects are likely to be high-mass X-ray binaries, many of them are located in the spiral arms Scutum and Norma (Walter *et al*. 2003; Kuulkers *et al*. 2005).

The high-energy sky is highly variable and many sources show a strong transient behaviour. *Integral* has performed many dedicated 'Target of Opportunity' observations of these unusual events. The high mass X-ray binary V0332+53 (discovered in 1973 with *Vela 5B*) was observed during another rare outburst by *Integral* early in 2005 (Kreykenbohm *et al*. 2005). Detailed analysis reveals the presence of a cyclotron line with three harmonics with energies of 24.9, 50.5, and 71.7 keV (see Figure 4). The derived magnetic field is $B \sim 3\times10^{12}$ G. Another binary system (X115+63) was observed during an outburst in September 2004 (Santangelo *et al.* 2005). Again, this system is a transient pulsar and *Integral* provided the highest resolution observation of cyclotron lines ever. Phase-resolved spectroscopy showed that the line energy varies during the pulse phase suggesting different configurations of the magnetic field in the emission region.

A great surprise was the detection by *Integral* of very hard emission from anomalous X-ray pulsars (AXPs). These systems were known (until *Integral*) as young pulsars, with soft spectra and very strong magnetic fields.

These AXPs (six systems are known) are also called magnetars ($B \sim 10^{15}$ G), being responsible for a sub-class of gamma-ray bursts: the so-called Soft Gamma Repeaters. *Integral* showed, for the first time, that the spectra of these AXPs are surprisingly very hard at energies above 10-20 keV (Kuiper *et al.* 2004). The hard spectra must have a magneto-spheric origin, i.e., they are not powered by the spin-down mechanism. In order to be consistent with higher energy observations by *CGRO*, these spectra must show a break or bend at higher energies, to be detected by *Integral* in future observations.

Observations of gamma-ray lines produced during nucleosynthesis processes are the main objectives for the SPI on board *Integral*. The 511 keV observations of the Galactic Centre region (see above) also revealed the existence of a weak disk emission which can be fully described by the positrons produced during the radioactive decay of ^{26}Al (mainly) and ^{44}Ti, two radioactive species produced during explosive nucleosynthesis in supernova explosions. ^{26}Al can therefore be regarded as a key-tracer of star formation. The line has been observed at high significance level in the Galaxy and, in particular, in the Cygnus region – an area of active star formation (Knoedlseder *et al*. 2004). The line is moderately broadened (3.3 keV at 1.8 MeV or 550 km s^{-1} – much broader than due to Galactic rotation alone) which could reflect the kinematics of the star-forming region in the ^{26}Al ejecta.

Cas A is the youngest known galactic supernova remnant (SNR) and ^{44}Ti is an important tracer for supernova processes. Its yield is a sensitive indicator of the mass cut, the energy and asymmetries involved in the supernova (SN) explosion. Observations of this line with energies at 68, 78 and 1157 keV are crucial to test SN explosion theories. ^{44}Ti emission has been observed by Integral-IBIS from the supernova remnant Cas A at 68 keV together with a first measurement of the continuum above 90 keV which is important for modelling this line. So far, the SPI has not detected a line, but there is an indication that the line may be broadened (Vink *et al.* 2005). Future work is in progress either to place more stringent upper limits on line broadening or to measure the line width, with further impacts on the physics of the explosion mechanism.

Thanks to its large field of view, *Integral* also observed the Tycho SNR during the Cas A observations. No lines have been detected as yet, but given the distance of 2.3 kpc and the observed 3σ upper limit of 10^{-5} cm^{-2} s^{-1}, the sub-Chandrasekhar models for SN Ia events, predicting a ^{44}Ti yield of $> 2\times10^{-4}$ solar masses can be excluded for Tycho SNR (Renaud 2005).

Very recently, an important discovery has been made by detecting line emission from the decay of ^{60}Fe, another product of nucleosynthesis during the end-points of stellar life. A flux of $3.7 \pm 1.1 \times10^{-5}$ ph cm^{-2} s^{-1} per line at 1173 keV and 1333 keV has been reported (Harris *et al.* 2005). Current nucleo-synthesis models for massive stars predict a rather large ^{60}Fe production so that the expected flux ratio between lines from ^{60}Fe and ^{26}Al should be of the order Fe/Al ~ 0.4 or larger. However, the observed value is smaller, namely 0.11 ± 0.03. This suggests that core collapse SNe may not be the dominant sources of Galactic ^{26}Al and that other sources prior to the collapse (massive winds from Wolf-Rayet stars?) should exist. This is a key question to be addressed by future mapping which should discriminate between source populations being responsible for the production of ^{26}Al and ^{60}Fe.

Turning to extragalactic science, Active Galactic Nuclei are also important targets for *Integral*. The central regions of these AGN comprise a central super-massive black hole surrounded by a torus of accreting matter. Depending on the inclination of the torus, it can hide the black hole and the hot accretion disk from the line of sight. Galaxies in which a torus blocks the light from the central accretion disc are called ‘Seyfert 2’ type, and are usually faint to optical telescopes. Another theory, however, is that these galaxies appear rather faint because the central black hole is not actively accreting gas and the disk surrounding it is therefore faint.

Using *Integral* and *XMM-Newton*, more evidence has been found that massive black holes are surrounded by a doughnut-shaped gas cloud, the torus. Depending on our line of sight, the torus can block the view of the black hole in the centre. Looking ‘edge on’ into this doughnut for the AGN NGC 4388, it was possible to see features never before revealed with such clarity. For example, some of the gamma rays produced close to the black hole are absorbed by iron atoms in the torus and are re-emitted at a lower energy, proof for seeing ‘reprocessed’ light farther out (Beckmann *et al*. 2004). Also, because of the line of sight towards NGC 4388, we know this iron was from a torus on the same plane as the accretion disk, and not from gas clouds ‘above’ or ‘below’ the disk.

Integral regularly observes Gamma-ray Bursts (GRB) as serendipitous sources in its large field of view. An automatic ground-based software system detects these GRB instantaneously and automatically alerts the science community world-wide to undertake crucial follow-up observations at other wavelengths. Thanks to this service, observations of a GRB that occurred on 3 December 2003 have been studied thoroughly by *Integral* and an armada of space and ground-based observatories. It has been concluded that this event, called GRB 031203, is the closest cosmic gamma-ray burst on record, but also the faintest (Sazonov *et al*. 2004). This important observation suggests that, prior to *Integral*, an entirely new population of sub-energetic gamma-ray bursts (which has to be large) has gone unnoticed.

It can be concluded that *Integral*, is performing very well. Thanks to its superb point source imaging capabilities at hard X-rays and its high-resolution spectroscopic capabilities in the nuclear line region, *Integral* during its first two years has produced already a number of significant discoveries. The science community is eagerly awaiting more data from the years to come.

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About the Author

Christoph Winkler is senior scientist at ESA. He is a member of the Research and Science Support Department at the European Science and Technology Centre (ESTEC) in Noordwijk (The Netherlands). He has extensive experience in the area of high-energy astrophysics, especially in gamma-ray astronomy. He was Co-Investigator for the COMPTEL experiment aboard the *Compton Observatory* and a member of the COMPTEL instrument team. As Study Scientist, he was responsible for the scientific mission design for future gamma-ray projects *GRASP* and *Integral*. Since 1993, he has been Project Scientist for ESA's gamma-ray observatory *Integral*. His research interests include the galactic centre and galactic structure, γ-ray line emission from point and diffuse sources and γ-ray bursts.

[2] http://integral.esac.esa.int/workshops/Jan2005