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2.7 Integral

Introduction

Integral was launched on 17 October 2002 into a highly elliptical 72 h orbit with an initial perigee of 9 000 km, an apogee of 154 000 km and inclination of 52º. Scientific observations are performed above nominal altitudes of 60 000 km (approaching the radiation belts) and 40 000 km (leaving the radiation belts). This ESA-led mission includes contributions from Russia (the Proton launch) and NASA (Goldstone ground station). Integral is currently delivering gamma-ray observations at high spatial and spectral resolution, in the 15 keV to 10 MeV energy range, using two main instruments: the SPI spectrometer and the IBIS imager. Both instruments provide spectral and spatial information, with SPI optimised for high spectral resolution ($E/\Delta E \sim 500$) in the energy range 20 keV to 8 MeV, and IBIS for high spatial resolution (a source location accuracy of < 1 arcmin). SPI has an array of 19 cooled Ge detectors, while IBIS has an array of 16 384 CdTe detectors (ISGRI), sensitive at 15 keV to 1 MeV, located above 4096 CsI crystals (PICsIT), working at 175 keV to 10 MeV. In addition, simultaneous X-ray (JEM-X, 3–35 keV) and V-band (OMC) optical monitoring is provided. All three high-energy instruments use the coded-mask principle to provide imaging information over large fields of view. The Integral Science Operations Centre (ISOC) is located in ESAC, Madrid. Mission operations are conducted from ESOC, Darmstadt and the nationally-provided science data centre (ISDC) in Versoix, near Geneva. The main ground station is at Redu, Belgium.

Mission status

Integral operations were originally approved for 2.2 years of operation with a design lifetime of 5 years. Integral moved beyond its design lifetime in October 2007. In order to plan for operations beyond this date, an independent review of operations (the Mission Extended Operations Review or MEOR) was conducted. The review focussed on the expected performances of the spacecraft, the instruments and ground segment, and examined a revised operations concept and the levels of support required from the nationally-funded instrument teams and data centre consortium. This revised operations concept strongly reduces costs by combining elements of the Integral and XMM-Newton Mission Operations at ESOC. With the reduced costs that this combined operations concept allows, the SPC recently approved operations until the end of December 2012, with further extensions possible (assuming that the technical status and scientific return remain high). Combined operations are running smoothly, with all systems and the ground segment performing as expected. At the current rate of consumption there is ample propellant for the approved lifetime. There has been no unexpected degradation of the solar arrays, batteries or any other system and there has been no loss of redundancy.

The particle background experienced by Integral is monitored via a dedicated counter (IREM). On the payload side, two of the 19 SPI detectors failed (in 2003 December and 2004 July) resulting in (to first order) a reduction in observing efficiency of ~10%. The SPI detectors are annealed (baked) about every 6 months to maintain the instrument’s very high spectral resolution. Owing to a slow change in performance, only one of the two identical JEM-X units is operated at any one time, thereby ensuring a suitably long lifetime. The other instruments are working as expected, with performances in line with those predicted before launch.

The major part of observing time is made available to the general astronomical community via calls for observing proposals. AO-5 was issued in March 2007 and covered 80% of the available observing time for an interval of one year. 160 proposals were received, resulting in an annualised over-subscription factor of 5.9. These included 22 Key Programme observation proposals. Key Programmes were

For further information, see http://integral.esa.int/

Table 2.7.1. Principal characteristics of the Integral scientific payload.

	SPI	*IBIS*	*JEM-X*	*OMC*
Energy range	20 keV - 8 MeV	15 keV - 10 MeV	3-35 keV	500-850 nm
Detectors/characteristics	19 Ge (each 6x7 cm) cooled @ 85K	16384 CdTe (each 4x4x2 mm); 4096 CsI (each 9x9x30 mm)	Microstrip Xe-gas detector (1.5 bar)	CCD + V-filter
Detector area (cm^2)	500	2600 (CdTe) 3100 (CsI)	2 x 500	2048 x 1024 pix
Spectral resolution	2.2 keV @ 1.33 MeV	9 keV @ 100 keV	1.3 keV @ 10 keV	–
FOV (fully coded)	16°	9x9°	4.8°	5x5°
Angular res (FWHM)	2°	12 arcmin	3 arcmin	17.6 arcsec/pix
10σ source location	1.3°	< 1 arcmin	< 30 arcsec	6 arcsec
Continuum sensitivity*	3×10^{-6} @ 1 MeV	3×10^{-6} @ 100 keV	1.2×10^{-4} @ 6 keV	18.2^{m} (10^{-3} s)
Line sensitivity*	5×10^{-6} @ 1 MeV	2×10^{-5} @ 100 keV	1.7×10^{-5} @ 6 keV	–
Timing accuracy (3σ)	129 µs	62 µs - 30 min	122 µs	var. in units of 1 s
Mass (kg)	1309	628	65	17
Power (W)	250	220	52	12
Telemetry allocation (kbit/s)	45	57	4	2

*sensitivities are 3σ in 10^5 s and $\Delta E/E = 0.5$, units ph cm^{-2} s^{-1} keV^{-1} (continuum) and ph cm^{-2} s^{-1} (line)

first introduced in a pilot study in AO-4 and are scientific investigations that require a very significant amount of observing time to achieve their scientific objectives. Since the fields of view of the Integral instruments are very large, these deep pointings can also provide information on a whole range of other targets visible within the fields of view.

The online data archive at the ISDC (*http://isdc.unige.ch/?Data+browse*) is regularly updated as new observations enter the public domain (1 year after they are received by the observer). In collaboration with the ISDC, the ISOC Science Data Archive (ISDA) (*http://Integral.esac.esa.int/isda*) was made publicly available in July 2005. The ISDA is based on the technology used to create the ISO and XMM-Newton ESA archives and provides users experienced with, for example, the XMM-Newton archive with a familiar interface to access Integral science products. Offline scientific analysis software for all the instruments (currently OSA 7.0) can be downloaded from the ISDC and installed on the user's own computer.

Scientific highlights

Asymmetric positron annihilation emission

A major scientific highlight is the Integral discovery of an asymmetric distribution of positron annihilation emission in the Galactic disc. Annihilation emission of photons with energy of 511 keV is produced via the annihilation of electrons with their

Table 2.7.2. Principal characteristics of the Integral mission.

Launch: 17 October 2002 by Proton into orbit of 72 h, 51.6° inclination, 9 000 km perigee height, 153 000 km apogee height. Start of science operations December 2002 (nominal duration 2 years, extended mission to December 2010 approved).

Science goals: compact objects; extragalactic astronomy; stellar nucleosynthesis; galactic structure; particle processes and acceleration; identification of high-energy sources.

Science operations:
- Integral Science Operations Centre (ISOC) at ESAC (Vilspa);
- Integral Science Data Centre (ISDC) in Versoix (CH);
- distribution of observing time:
  - 1st mission year: 35% guaranteed time, 65% open time (via AO)
  - 2nd mission year: 30% guaranteed time, 70% open time (via AO)
  - 3rd-5th mission years: 25% guaranteed time, 75% open time (via AO)
  - 6th mission year: 20% guaranteed time, 80% open time (via AO)
  - 7th mission year and beyond: 100% open time (via AO)

Spacecraft:
- 3-axis stabilised (all errors 3σ; instruments point along x-axis, y-axis is along length of solar arrays):
  - absolute pointing error: 5 arcmin (y,z), 15 arcmin (x)
  - absolute pointing drift (10^5 s): 0.6 arcmin (y,z), 2 arcmin (x)
  - relative pointing error (10^3 s): 0.3 arcmin (y,z), 1 arcmin (x)
  - absolute measurement error: 1 arcmin (y,z), 3 arcmin (x)
- Data rate: 108 kbit/s (science telemetry)
- Power (payload): 690 W
- Spacecraft size: 3x4x5 m (solar arrays stowed; 16 m span deployed)
- Mass: about 4000 kg at launch; 3500 kg dry; 520 kg hydrazine propellant

Operations:
- Mission Operations Centre: ESOC (Darmstadt, D)
- Data transmission: S-Band, ground stations: Redu (B), Goldstone (USA)
- Mission lifetime: 2 years nominal, 5 years technical design life

antimatter particles, the positrons. A key question in high-energy astrophysics is to identify the astrophysical source which is producing about 10^{43} positrons per second, in order to match the observed intensity and distribution. Integral observations have shown for the first time that the inner Galactic disc emits an emission pattern which is lopsided with respect to the emission from the central bulge region. The observed imbalance matches the distribution of a population of bright hard low-mass X-ray binary systems and suggests strongly that these binaries are churning out at least half of the antimatter, and perhaps all of it. The reported Integral detection of an 'annihilation-asymmetry' represents a significant step forward toward a solution to one of the major outstanding problems in high-energy astrophysics.

First hard X-ray determination of the cosmic diffuse background since 1970s

Using a unique observing technique, Integral successfully observed the cosmic diffuse X-ray background (CXB) radiation in the hard X-ray range. The Earth was used as an occulting disc. Since it is impossible to point the satellite while the illuminated part of the Earth blinds the star trackers, Integral was pointed at a stationary position in the sky and the Earth drifted through the field of view of the

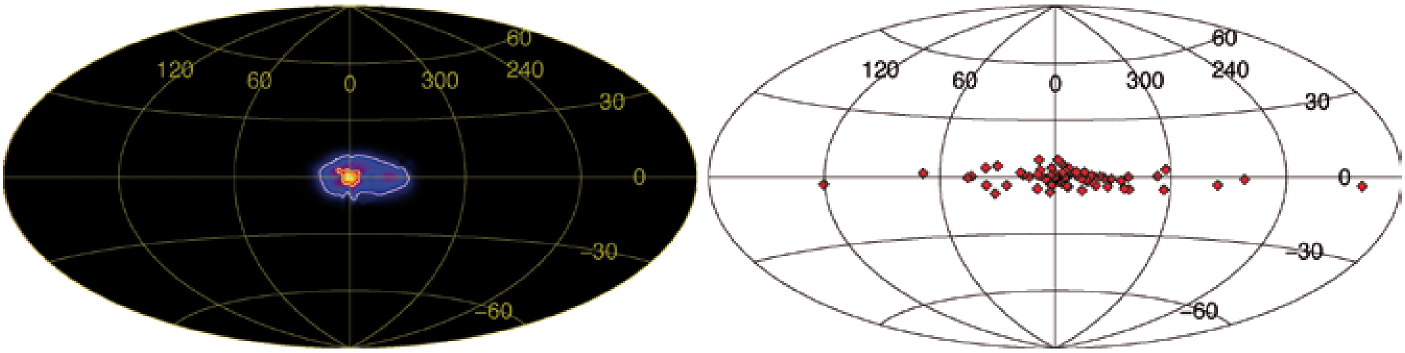

Figure 2.7.1. The left-hand panel shows the glow of 511 keV gamma rays coming from the annihilation of electrons by their antimatter counterparts, the positrons. The map shows the entire sky, with the galactic centre at the middle. The emission can be seen extending towards the right-hand side of the map. The right-hand panel shows the distribution of hard low mass X-ray binary stars. This stellar population has a distribution that matches the extent of the 511 keV map. (ESA/Integral/MPE) (G. Weidenspointner *et al., Nature* 451, 159, 2008)

instruments. The residual emission obtained in Integral's large field of view was attributed to the diffuse background after correcting for emission and scattering of the Earth atmosphere. The resulting spectrum, the first accurate CXB determination since HEAO-1 in the 1970s, shows a smooth transition from low energy X-ray data below 5 keV, towards a peak at around 25 keV, with a slightly higher normalisation (10%) than observed previously.

What is the origin of the observed emission? Initial Integral AGN surveys concluded that the fraction of Compton-thick AGN is less than 10% and insufficient to account for the CXB emission, at least in the local ($z = 0.02$) Universe. Surveys at lower energies demonstrated that in the classical X-ray band, the CXB can be largely explained by AGNs with an increasing fraction of absorbed sources. Extrapolating from this, one would have expected a much larger contribution from heavily shrouded AGNs than now found by the different Integral studies. Possibly shrouded sources are more frequent at higher red shifts where they would be too weak to detect with the current sensitivity limits. Or another population of even more densely shrouded sources could exist.

The keV to TeV connection

Integral is conducting a strong collaboration with ground-based very-high-energy telescopes (HESS, MAGIC). This is of paramount importance to identify the nature of sources which emit at keV but also at TeV energies, such as pulsar wind nebulae or supernova remnants. HESS J1616-508 is one of the brightest sources in the TeV sky and is located in a complex region containing two known supernova remnants: RCW 103 and Kes 32, which do not coincide with the HESS extension. Recent observations with Integral/IBIS have revealed that a young, nearby and energetic pulsar, PSR J1617-5055, is a powerful emitter of soft gamma-rays in the 20–100 keV energy domain. The Integral detection, combined with the lack of any low energy counterpart to the HESS source obtained with Swift, XMM-Newton and BeppoSAX data covering the TeV region, make the pulsar PSR J1617-5055, slightly offset near the edge of the error circle of the HESS location, the only likely candidate for the TeV emission. This hypothesis is also supported by the fact that the Integral spectrum smoothly connects with the BeppoSAX and XMM-Newton spectra, and that the luminosity is consistent with that expected from a young radio pulsar. The relative sizes of the X/gamma-ray and VHE sources are consistent with the expected lifetimes against synchrotron and Compton losses for a single source of parent electrons emitted from the pulsar. This suggests that the HESS J1616-508 source is driven by PSR J1617-5055 in which synchrotron and inverse Compton processes combine to create the observed morphology of a broadband emitter from keV to TeV energies.

Diagnosing the trace of super-massive stars

During their lifetime, massive stars synthesise heavy elements including ^{60}Fe and ^{26}Al. ^{60}Fe is a radioactive isotope produced in convective shells of massive stars by neutron capture reactions. Theoretical predictions of ^{60}Fe yields are quite uncertain, due to uncertainties in nuclear reaction rates and neutron sources and stellar structure. With a 2.2 My radioactive lifetime, ^{60}Fe accumulates in the interstellar medium after it is ejected by the core-collapse supernova, which ends the massive star's life shortly after ^{60}Fe has been synthesised. SPI on Integral measured the two gamma-ray lines at 1.173 MeV and 1.332 MeV resulting from the decay of ^{60}Fe in interstellar space. The spectrum obtained is the most significant detection of this isotope to date, improving upon previous hints from RHESSI and earlier SPI measurements. ^{60}Fe nucleosynthesis is a key diagnostic of the structure of massive stars in their late stages. In particular, the ratio of ^{60}Fe to ^{26}Al gamma-rays is a convenient relative diagnostic, if both isotopes indeed originate predominantly from massive stars. Models predicted that this ratio would be in the range 10–100%, and it is now measured by SPI as (15±6)%. Refinements of models are underway, in particular re-evaluating nuclear reaction cross sections and beta-decay lifetime.

Soft gamma repeaters and gamma-ray bursts

A small subset of the classical gamma-ray bursts (GRBs) form the group of so-called Soft Gamma-ray Repeaters (SGRs), as they have predominantly soft spectra and recurrent outbursts. Persistent emission above 20 keV was never detected from SGRs before Integral. Deep observations with IBIS showed for the first time that the two SGRs that have been active in the last couple of years (SGR 1806-20 and SGR 1900+14) also have a persistent hard emission extending up to 100 keV, with a luminosity of about 10^{36} erg/s in the 20–100 keV range. SGRs and Anomalous X-ray Pulsars (AXPs) are believed to be magnetars, i.e. slowly rotating (P~5–10 s) neutron stars powered by extremely high magnetic fields (B~10^{15} G). An important discovery was the fact that several AXPs also showed pulsed emission up to ~150 keV. Integral obtained more data describing the broad band spectra of five magnetars (SGRs and AXPs). While the AXP spectra are characterised by soft spectra at low energy and a steep hardening above 10–20 keV, the SGRs show the opposite behaviour. The difference between the two SGRs, SGR 1900+14 being much softer than SGR 1806-20, could be due to the different activity level of the two sources, with the former being in quiescence from November 2002 up to March 2006 and the latter in a moderately active state.

Integral continues to be an important monitor to provide instantaneous accurate location data for GRBs occurring in its large FOV (about one per month) for other space- and ground-based observatories. However, when GRB 030406 exploded in early April 2006, Integral was pointing at about 36 deg away from the GRB location. Although the event occurred far outside the IBIS partially-coded field of view, it was possible to reconstruct an image of the event using the radiation that passed through the side veto shield of IBIS via Compton imaging techniques. This technique utilises the double scatter process of the photons in the two detection layers of IBIS, allowing determination of the energy and source location of the GRB photons. This Compton imaging technique is ideally suited for powerful GRBs with hard (power law) spectra and has been successfully applied to several GRBs already. The expected GRB rate

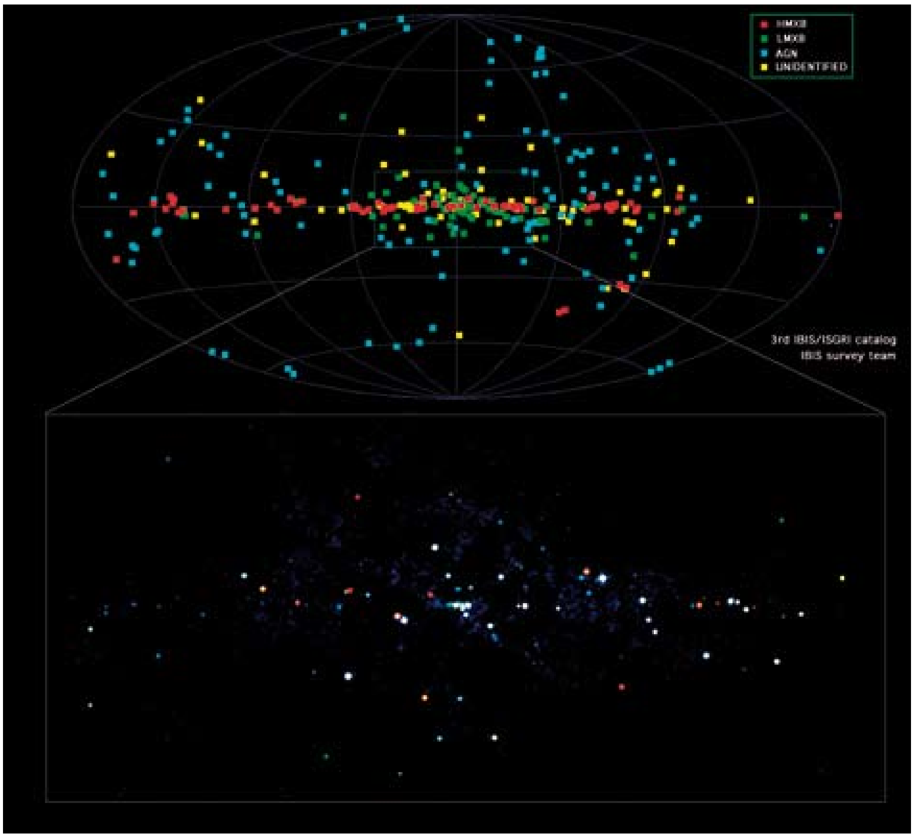

Figure 2.7.2. The upper panel shows the sky distribution of four of the main soft gamma-ray source populations observed in the third Integral/IBIS survey catalogue. This newly-released catalogue contains 421 sources. Of the known systems, low-mass X-ray binaries (LMXBs) are old systems mainly populating the galactic bulge, high-mass X-ray binaries (HMXBs) are younger systems seen along the galactic plane, and the active galactic nuclei (AGNs) are extragalactic sources seen over the whole sky. Around one in four of the sources seen by Integral are unidentified, and their distribution is also shown. The lower panel is a false colour image of the central region of our galaxy. This is a composite image based on all-sky IBIS/ISGRI maps in three energy windows (between 17 and 100 keV) and represents the true 'X-ray colours' of the sources. Red sources are dominated by emission below 30 keV, while blue sources have harder spectra, emitting strongly above 40 keV. (IBIS survey team, A Bird *et al., ApJSS* 170, 175, 2007)

is about 2 to 5 events per year. This non-standard imaging technique has also been successfully applied to the analysis of solar flare data, which due to the pointing constraints of the spacecraft always occur far outside the FOV.

The fastest spinning neutron star

Integral, in collaboration with NASA's Rossi X-ray Timing Explorer (RXTE), has detected what appears to be the fastest spinning neutron star yet. The neutron star XTE J1739-285 was discovered during one of its active phases on 19 October 1999 by RXTE. While Integral was routinely monitoring the bulge of the Galaxy, XTE J1739-285 recently started to come back to life and Integral discovered the first short bursts of X-rays from the object. During the brightest burst, oscillations were taking place at a frequency of 1122 Hz, the highest spin frequency ever recorded. The exact breakup speed depends on the internal conditions of a neutron star, which are not precisely known. The 1122 Hz detection places a serious constraint on neutron star models.

Integral source catalogues

The third Integral/IBIS survey catalogue has been released. The scientific data set is based on more than 40 Ms of high-quality observations performed during the first 3.5 yr of Core Programme and public IBIS/ISGRI observations. Compared to previous IBIS/ISGRI surveys, this catalogue includes a substantially increased coverage of extragalactic fields, and comprises more than 400 high-energy sources detected in the energy range 17–100 keV, including both transients and faint persistent objects that can only be revealed with longer exposure times. Around 25% of the sources seen by Integral are yet unidentified.

High-mass X-ray binaries: detection of new classes

X- and gamma-ray sources are often enshrouded in material that can suppress soft X-ray photons (typically 1–5 keV) but allow more energetic photons to permeate through. Because its soft gamma-ray imager ISGRI operates above 20 keV, Integral is unhindered by photoelectric absorption (N_H). Therefore, Integral is discovering many new heavily-absorbed sources that were missed by previous X-ray surveys. Analysis of recent Integral sky surveys resulted in 16 highly-obscured HMXB ($N_H \geq 10^{23}$ cm^{-2}), thereby increasing the number of known highly-obscured galactic sources from 9 to 25, and amplifying the asymmetric location in the spatial distribution of absorbed sources: the Norma Arm harbours a disproportionately large share of obscured sources. The Norma Arm is the region of the Galaxy that features the highest formation rate of OB super-giant stars. These are the precursor stars to the growing class of heavily-absorbed HMXB that Integral is well suited to find.

Integral has also discovered a new class of X-ray fast 'transient' binary stars, undetected in previous observations: the so-called 'super-giant fast X-ray transients' (SFXTs). The new class of double star systems is characterised by a very compact object that produces highly-energetic, recurrent and fast-growing X-ray outbursts, and a very luminous 'super-giant' companion. They show short outbursts with very fast rising times – reaching the peak of the flare in only a few tens of minutes – and typically lasting a few hours only. This is the main difference from most other observed transient X-ray binary systems, which display longer outbursts, lasting typically a few weeks up to months.

Before the launch of Integral, only a dozen X-ray binary stars containing super-giants had been detected. Actually, it was believed that such high-mass X-ray systems were very rare and that only a few of them would exist at a time, since stars in super-giant phase have very short lifetimes. However, Integral's data combined with other X-ray satellite observations indicate that transient super-giant X-ray binary systems are probably much more abundant in our Galaxy than previously thought. In particular, Integral is showing that such SFXTs form a wide class that lies hidden throughout the Galaxy. At the time of writing Integral has discovered eight new SFXTs, and analysis for another 20 candidates is proceeding. Due to the transitory nature, in most cases these systems were not detected by other observatories because they lacked the combination of sensitivity, continuous coverage and wide field of view of Integral.

Accreting white dwarf binaries

Nearly 25% of the Integral catalogue sources (see above) are still unidentified. It is now confirmed that systems containing white dwarfs also contribute significantly to the galactic high energy diffuse emission (see next section). A detailed study of such a new source (IGR J00234+6141) has led to an identification with a cataclysmic variable, a low mass binary system containing a highly-magnetised white dwarf, also called 'Intermediate Polar system' (IP). The Integral spectrum is well described by a thermal emission at a temperature of 30 keV. Such high temperatures are reached at the base of an accretion column above the white dwarf. About 5% of the Integral sources have already been identified with IPs, and IGR J00234+6141 shows that more such faint systems probably exist. As the white dwarfs are much more numerous than the neutron stars, it is anticipated that these systems represent a significant fraction of the unresolved high-energy diffuse emission from our Galaxy.

Diffuse galactic ridge emission (GRE)

The nature of the GRE is under scientific debate since its discovery in the 1970s. It is observed as extended emission along the Galactic disc with a bulge near the centre. The question was: is the GRE truly diffuse or is it composed of a large number of unresolved point sources? Recently it was shown that there are good reasons to believe that the GRE (or at least a dominant fraction of it) is due to a large number of very weak X-ray sources: accreting white dwarf binaries and coronally active stars. The implications of this conclusion are:

i) a prediction of the spectral shape of the ridge emission, and

ii) the spatial distribution of the GRE.

Regarding (i), the spectrum of the ridge emission should have an exponential cut-off at energies higher than ~20 keV, which approximately corresponds to the proton binding energy of the white dwarf, and (ii), the spatial distribution of the GRE should trace the density distribution of galactic stars.

These predictions have now been verified by analysing Integral observational data obtained during its four years of operation. It has been possible to map the weak hard-X-ray glow of the Galaxy and measure its spectrum. The map does not correlate well with the gamma-ray map of the Milky Way below 100 keV, strongly suggesting that X-ray emission is not generated by the cosmic ray interactions with ISM. Instead, the intensity of the GRE in hard X-rays traces well the stellar mass density distribution, thus providing strong support to the idea that the bulk of GRE is provided by weak compact sources. In particular, for the considered 17–100 keV energy band, the dominant contribution to the GRE should come from accreting white dwarf binaries. This result was further strengthened by the detection of a high energy cut-off (60 keV) in the ridge spectrum.

However, Integral SPI observation of the spectrum at higher energies (> 100 keV) shows that besides the clear diffuse (and line) annihilation signal around 200–511 keV there also exists an underlying (power law) spectral component extending up to the MeV range, smoothly joining the higher energy data from Compton GRO above 1 MeV. The entire diffuse emission above 100 keV up to 30 MeV cannot satisfactorily be explained by interstellar processes (cosmic-ray particles interacting with interstellar matter). That creates new questions about the change in origin of the galactic X-ray background from point sources to truly diffuse emission of the interstellar gas. Are we observing a hidden population of undetected point sources (e.g. hard pulsars or CVs), or is the emission truly diffuse?