INTEGRAL Confirmation and Extension 2012: Science Case

1 - Science Case

1.1 Mission impact and metrics

The observing programme, established through annual Announcements of Opportunity (AO), includes both deep (>1 Ms) and multi-year Key Programme observations, complemented by flexible Target of Opportunity observations. The continued community interest is reflected in the over-subscription in observing time for new observations in 2013, which remains high (3.3). To fully exploit the entire field of view, users also compete during a second AO phase for data rights on targets, which were not initially considered in the accepted observing proposals, but which are covered by these observations. This approach allows the most efficient and timely exploitation of the entire field of view data by various scientific teams: on average, 10 distinct scientists/teams work on exploiting the science of each observation.

INTEGRAL observations have resulted in 690 refereed papers and a total of 1950 publications (until June 2012): an increase of 145 (refereed) and 632 papers (total), respectively, since the previous extension request in 2010. At least 88 PhD theses related to INTEGRAL science have been completed since launch (14 more since 2010), and another 23 PhD theses are on-going (see appendix B). During 2011 an average of 7 TByte of scientific data was downloaded per month from the INTEGRAL archives (2.2 TByte/month during 2009) at the ISDC, ESA/ESAC, NASA/HEASARC, and IKI/RSDC. More than 260 unique visitors per month were counted (230/month in 2009).

INTEGRAL has vastly increased the number of known sources in the hard X-ray (now > 1000). Equally important, it has also massively increased our knowledge about the nature of many individual sources, with about 250 of the new discoveries now firmly identified and studied to great detail.

Selected INTEGRAL key achievements since launch include:

(1) The first large-scale sky-map at 511 keV (electron-positron annihilation).

(2) The first measurement of the true fraction of Compton-thick AGN.

(3) The discovery of: (i) a new class of relativistic binaries: compact objects enshrouded by a massive star stellar wind (highly absorbed galactic HMXB); (ii) a new regime of intermittent accretion in wind-fed relativistic binaries (Supergiant Fast X-ray Transients); (iii) dominance of accreting white dwarfs in "diffuse" galactic ridge hard X-ray emission; (iv) hard spectral tails in extremely magnetised neutron stars - likely observational appearance of $e^{\pm}$ pairs dominated fireball; (v) the most distant QSOs seen in hard X-rays; (vi) a population of faint GRBs with long spectral lags.

(4) The detection of: (i) ^{44}Ti gamma-ray lines from supernova Cas A; (ii) hard X-ray emission from various compact objects; (iii) polarised hard X-ray emission in Crab and in GRB 041219a; (iv) cyclotron line energies correlated with the height of the accretion column; (v) pulsed hard X-ray emission up to ~150 keV from rotation-powered pulsars.

(5) INTEGRAL furthermore (i) proved the Galaxy-wide origin of the ^{26}Al line; (ii) determined the ^{26}Al/^{60}Fe yield ratio constraining SN models; (iii) determined independently the Galactic core-collapse SN rate; (iv) traced the past activity of Sgr A* via its Compton echo; (v) determined the hard X-ray luminosity function of AGN.

The following is a list of some of the important scientific results obtained during the last two years: (i) the Crab nebula/pulsar is not a stable in-flight calibration source; (ii) nuclear ^{44}Ti line emission from SN 1987A; (iii) polarised high energy emission from Cyg X-1; (iv) MeV to GeV emission from a SFXT; (v) strong soft γ-ray emission during magnetar outbursts; (vi) diffuse hard X-ray emission from the Vela pulsar wind nebula and (vii) very stringent limits on the violation of the Lorentz invariance principle.

1.2 Confirmation of scientific performance for 2013–2014

As discussed in Sect. 3, the scientific performance of the mission in 2013 and 2014 is expected to be effectively unchanged from that presented at the last extension request in 2010 (ESA/SPC(2010)21). Thus it is expected that the scientific objectives defined for this interval in the last extension case will be accomplished.

1.3 Science case for the extension interval 2015–2016

The key science areas of INTEGRAL are expected to be (A) gamma-ray lines from nucleosynthesis in supernovae and novae, and from $e^{\pm}$ annihilation, (B) emission mechanisms in white dwarfs, neutron stars, and stellar black holes, (C) supermassive black holes in Active Galactic Nuclei (AGN), and (D) gamma-ray bursts.

(A1) Electron-positron annihilation emission: INTEGRAL maps 511 keV emission at large scales ([K05], see appendix A for references). The origin of the positrons producing this line is a 40-year old mystery [P11]. Possible physical channels range from conventional nucleosynthesis up to decay of dark matter particles. The morphology (Fig. 1, Fig. 2, for figures see appendix A) of the 511 keV emission as measured by INTEGRAL is already constraining possible production as well as positron-propagation models [W08], [C11].

(A2) Diagnostics of massive-star interiors and supernova explosions: Gamma-ray lines show freshly created elements during nucleosynthesis processes, which power stellar life and also supernova emission. INTEGRAL observes line emission from long-lived (~ 1 Myr) ^{26}Al, ^{60}Fe, as well as from short-lived ^{44}Ti. From the measured total mass of ^{26}Al an independent determination of the galactic core-collapse SN rate can be obtained [D06]. Line emission from ^{60}Fe provides an important diagnostics for massive-star structure models during their evolution [W07]. Non-detections of gamma rays from the ^{56}Ni decay chain in SN 2011fe constrain models where ^{56}Ni ejecta would be distributed far into the outer envelope in SNIa [I11], [I12].

(A3) Diagnostics of supernovae feedback in the ISM: Gamma-ray lines from freshly created elements during nucleosynthesis processes provide unambiguous signals from massive stars and their supernova explosions, as they blast into the surrounding interstellar medium. Gamma rays from ^{26}Al are Doppler-shifted due to large-scale galactic rotation, directly proving its Galaxy-wide origin [D06]. This Doppler shift encodes kinematic motion of the hot phase of the ISM, and has been found to move at higher velocities than observed from the parental molecular clouds (Fig. 3). This provides a new look at massive-star feedback and blow-outs from dense clouds in the bar of our Galaxy [K12].

In the early part of the mission, SPI detected gamma-ray lines. Now, detailed studies of line shapes and spatial distributions quantitatively test specific astrophysical models/processes. Future gamma-ray line observations are expected to advance these key science topics:

• The morphology of the annihilation emission near the galactic centre and in the bulge-like extended central region, and in more regions along the galactic disk, where known candidate sources reside [P11]. These will be key to determine the origin of the positrons.

• Disentanglement of more ^{26}Al source regions in the Galaxy, thus measuring ^{26}Al yields from massive stars in a larger sample of associations (e.g. [M10], [V12]).

• Test if the spatial distribution of the ^{60}Fe line emission is consistent with that of the ^{26}Al emission, to consolidate constraints on massive-star structure from these products.

• Measure the dynamics of the hot ISM in the inner Galaxy, Cygnus, or other ^{26}Al-bright regions with a velocity resolution of ~100 km s^{-1}. Similarly, provide a unique diagnostic on black holes in X-ray novae through detecting potentially red-shifted 511 keV line emission.

• Study the inner regions of a core-collapse supernova (SN) via ^{44}Ti gamma-ray line emission [R06]. More exposure is likely to reveal other ^{44}Ti candidates along the galactic plane, and improve for SN 1987A [G12]. This will guide future NuSTAR observations of ^{44}Ti, and together constrain core-collapse supernova yield models.

• Similarly, provide tighter limits on ^{56}Ni lines from SN type Ia. We are awaiting a nearby and over-due SN Ia for unique constraints directly from the gamma-rays (Fig. 4). Studies of gamma rays from ^{22}Na and ^{7}Be will establish INTEGRAL's legacy on nova nucleosynthesis. There is a significant chance of both a nearby SN Ia [L12] and a nova event [Da06], [H04] during the extended mission operations phase. We might well learn more about such explosions from one object seen in gamma-ray lines than from all previous objects combined and INTEGRAL will be the key contributor to that knowledge.

(B1) Activity of the supermassive black hole in our Galaxy: Over the last few years, INTEGRAL has detected the fading luminosity of the molecular cloud Sgr B2 (Fig. 5, Fig. 6) [T10] which is considered to be the echo of past activity of Sgr A* [R04], now seen as a reflection off the molecular cloud. With measurements of the Fe K-line variability from surrounding clouds, monitoring of the hard X-ray emission is essential in studying the galactic super-massive black hole. Interest in such monitoring recently increased due to the discovery of the small gas cloud G2 on an orbit almost directly into Sgr A* [G12], [Bu12].

(B2) Highly absorbed and fast transient massive X-ray binaries: INTEGRAL has discovered a large number of relativistic sources, strongly absorbed at X-rays (Fig. 7) [C03], [L05] and continues to do so. Often such sources also demonstrate violent flux variability (so called supergiant fast X-ray transients), which is being detected due to INTEGRAL's unique survey capabilities [N06], [S06], [S11]. These sources might be very numerous and comprise a large fraction of neutron star binaries in our Galaxy. The unbiased search for such sources and their future detailed spectral and temporal study will provide important insights into our understanding of evolution of stellar populations in the Galaxy.

(B3) Cyclotron lines and structure of accretion column on neutron stars: For magnetised neutron stars (NS) matter is channelled by their super-strong magnetic fields (up to 10^{15} G) into an accretion column and stopped near the NS surface by a standing shock. Hard X-ray emission from this heated matter penetrates through the plasma threaded by the magnetic field and displays cyclotron absorption lines (Fig. 8). INTEGRAL studies [T06], [K12] showed variations of these line energies correlated with source luminosity [B12]. Further discoveries will allow tests of models for the structure of the accretion column [B10] and to distinguish between “classic” neutron stars (10^{12} G) and magnetars (~10^{15} G).

(B4) Spectroscopy and polarimetry of sources in hard X-rays/soft gamma rays: Most of the X-ray emission of relativistic objects originates in thermal processes with temperatures from ~0.5 keV to 30 - 70 keV. However, at energies above ~100 keV, a growing set of sources with non-thermal emission is being detected by INTEGRAL [P06]. INTEGRAL's capabilities in this energy range will remain unmatched for a long time. The recent measurement of the polarisation of soft gamma emission from Cyg X-1 [L11], [J12] supports the idea that such emission originates from non-thermal processes (Fig. 9). Therefore, more precise spectral and polarisation measurements (Fig. 10) will be essential to test models of relativistic jets near black holes, e.g. [Z12].

(B5) Variability of emission of Crab nebula: The Crab nebula is considered to be one of the most stable and brightest sources on the high-energy sky and has been used, for more than 30 years, as a calibration source. However, recent studies of the Crab nebula emission by different observatories, including INTEGRAL, showed that its flux varied by ~ 7% over the last 5 years (Fig. 11, [W11]). The origin of these variations and their relation to very high-energy flares is not yet clear. Future precision monitoring of this source in coordination with as many as possible other high-energy observatories may shed light on this question.

(B6) Magnetars in outburst: One of the most unexpected discoveries of INTEGRAL was strong hard X-ray/soft gamma ray emission of magnetars (Fig. 12, Fig. 13), [Ku06], [Ku12].

The data collected so far trace their spectra up to ~300 keV with no apparent cut-off. New physical models for these hard tails (e.g. [B09], [B10]) predict a cut-off at several hundred keV, to be tested with future observations at energies accessible only to INTEGRAL.

(B7) Emission of the Milky Way: The global Galactic emission above 50 keV is no longer believed to be dominated by compact X-ray sources (see [L04], [Kr07]) but produced by the interaction of cosmic ray particles with the interstellar medium (e.g. [P11], [B11]). The surface brightness of this emission is very low and only INTEGRAL is able to measure it, due to the stable and low instrumental background together with the ability to disentangle individual sources from the diffuse glow of the Galaxy (Fig. 14). Due to the extreme faintness of the emission, very long observing times must be accumulated. One of the most important aspects of this extended emission is its spatial variation across the Galaxy, which is now being studied by customised INTEGRAL observing programmes [Kr10], [Kr12], [B11], which need to be continued to build up a legacy dataset for the study of cosmic ray interaction.

(C1) Understanding AGN populations: the high-energy emission of AGN is due to thermal Comptonisation of soft photons by a mildly relativistic surrounding plasma of low optical depth [M09], [B09]. The latest INTEGRAL catalogues ([B09], [M12], [K12]) contain about 300 AGN, spanning a wide range in redshifts ($0.0014 \leq z \leq 3.7$), luminosities (10^{40}-10^{48} erg/s, Fig. 15) and black hole masses (10^4-10^9 $M_\odot$). Covering such a large parameter space, the INTEGRAL AGN sample is ideal for population studies. Furthermore, avoiding the bias due to the obscuration at lower energies, it includes now all types of AGN [P11], [M12], [Ma12]. New results, as the unexpected detection of H_2O maser sources in INTEGRAL objects, will provide unique insights into the physics of AGN [T11], [C11].

(C2) Highly-absorbed AGN: INTEGRAL has been used to probe extensively the Compton-thin regime and to discover new Compton-thick sources (Fig. 16) [M12]. A recent finding indicates that ~50% of all AGN are absorbed ($N_H > 10^{22}$ cm^{-2}) but only ~4% to 7% are Compton-thick ($N_H > 1.5\times10^{24}$ cm^{-2}) [B09], [M12]. Taking the loss of highly absorbed AGN at higher redshifts into account, the above figures become 80% (absorbed) and 20% (Compton-thick), respectively. It is expected that INTEGRAL will continue to find more obscured AGN.

INTEGRAL measurements have shown a trend of a decreasing fraction of absorbed AGN with increasing hard X-ray luminosity [M12] (Fig. 17). In the next 4 years, ultra-deep (≥10 Ms) observations will determine whether this is a pure luminosity effect, or related to evolution. These will be among the most sensitive observations above 100 keV for decades to come. INTEGRAL's sub-mCrab sensitivity at 50 keV will be complemented, at lower energies, by extremely sensitive NuSTAR observations, shedding new light on the AGN torus/reflection properties and their evolution. This synergy will be particularly important for the study of the primary continuum in a statistically significant sample of bright AGN.

(C3) The Cosmic X-Ray Background (CXB) population synthesis: joint INTEGRAL-NuSTAR observations will become a powerful tool to disentangle cosmological questions such as the AGN contribution to the CXB. INTEGRAL has already established (Fig. 18) a first direct comparison between the collective hard X-ray spectral energy distribution (SED) of local AGN and the CXB spectrum in the 3–300 keV energy range [S08], [T10]. Further observations will allow a unique investigation of the contribution of blazars to the diffuse continuum in the 100–300 keV range, where the contribution of Seyferts is decreasing exponentially. Additional INTEGRAL observations, using the Earth as a "blocking device", will be performed, to determine the integrated CXB flux (see [C07], [T10] for initial results).

(C4) The most extreme BHs: a major objective for the coming years will be to find more "extreme" hard X-ray selected blazars, such as the TeV emitting BL Lacs having small jet power and a synchrotron peak at 10's of keV or more. INTEGRAL is discovering QSO's with the most powerful jets [G11] (Fig. 19), largest black hole masses, most luminous accretion disks, and a Compton peak in the MeV region [Ba07], [Ba12]. This is providing a new perspective for jet-dominated sources, starting to probe the earliest supermassive black holes [Ba12]. Finally, the study of misaligned radio galaxies (Fig. 20) will be important, in order to clarify why some of these sources are seen by Fermi/LAT while others are not [B11], and therefore to probe if jets are made of e± pairs [G12].

(C5) Soft gamma-ray emission of AGN: INTEGRAL will provide unique coverage above 100 keV in synergy with observatories operating from GeV to TeV, essential to distinguish between different jet emission mechanisms. Other multi-waveband studies will also benefit from INTEGRAL data on AGN in conjunction with radio measurements to disentangle the jet/disk-corona contribution in radio loud and radio quiet objects. Fitting IR spectra of hard X-ray selected AGN with clumpy torus models may be the only feasible way to estimate the intrinsic distribution function of torus covering factors [E12], [R11], [Br12].

INTEGRAL will add new fundamental information to our overall knowledge of supermassive black hole activation, unification, and evolution. It will provide an invaluable database to select scientific targets for hard X-ray missions, such as NuSTAR and ASTRO-H. The high-energy survey legacy of INTEGRAL will therefore remain unique for the next decades and the "decade-long" unbiased INTEGRAL survey will be of seminal importance for extragalactic astronomers, comprising hundreds of sources by the end of 2016.

(D1) INTEGRAL is the most sensitive mission for studying faint Gamma-Ray Bursts (GRBs) in the 20 – 1000 keV energy range (Fig. 21). Arc-minute positions of GRB (Fig. 22) in the INTEGRAL/IBIS field of view are derived and distributed in real-time by the INTEGRAL Burst Alert System (IBAS) [M03] at a rate of about 10 GRB per year (87 to date), the weakest GRBs with a fluence of $\sim 5 \times 10^{-8}$ erg cm^{-2} in the 20–200 keV range [V09]. Follow-up observations of these GRB by Swift, XMM-Newton, and by ground-based observatories revealed more than 50 X-ray, optical, and/or radio counterparts with redshifts between z = 0.105–3.793. The INTEGRAL/SPI anticoincidence (veto) system, the largest GRB detector in operation, detects one GRB about every 3 days [S12] (Fig. 23). INTEGRAL will continue to play a key key role in identifying more events like the giant flares from extragalactic magnetars in M81 and M31 [F07], [M08], [A08].

(D2) INTEGRAL is essential to investigate the fraction of GRB with long spectral lags, which appear to be a distinct low-luminosity population, which have been observed in the direction of the super-galactic plane [F08] – an important INTEGRAL discovery. The nature of this population will be further explored in the next four years benefitting from the lower background and the recently implemented lower GRB detection threshold.

(D3) The detection of hard X-ray polarisation in GRB 041219A with INTEGRAL, the only high energy polarimeter operative in the next decade, provides information on the physical mechanism by which the central engine of a GRB emits the huge observed energies, a presently unresolved but crucial issue [G09], [K07], [Mc07]. The observation of another polarised GRB, more distant (>~ 100 Mpc) than GRB 041219A, would test the Lorentz invariance beyond the limit already established by INTEGRAL [L11].

1.4 Complementarity and uniqueness

INTEGRAL is covering the 3 keV to 10 MeV energy band, with excellent sensitivity during long and uninterrupted observations of a large field of view (~100 □°), with ms time resolution, keV energy resolution and polarimetry capabilities. INTEGRAL therefore connects X-ray missions such as XMM-Newton, Chandra, Suzaku, Swift, NuSTAR, eRosita (2014), and ASTRO-H (2014) with high-energy gamma-ray observatories such as Fermi, AGILE, and ground-based gamma-ray telescopes such as HESS. INTEGRAL will remain the only observatory worldwide providing these capabilities to the community in this decade.

Numerous new astronomical detectors dedicated to the violent Universe have recently become – or will soon be – operational. These include new optical/IR and large radio telescopes, Cherenkov telescope arrays, ultra high-energy cosmic-ray detectors, neutrino detectors, and gravitational radiation detectors. Simultaneous observations of violent phenomena in different bands of the electro-magnetic spectrum, along with gravitational radiation and neutrino measurements, will create new opportunities for astrophysics. INTEGRAL will play an important role in these investigations.

1.5 INTEGRAL Users Group recommendation

The INTEGRAL Users Group unanimously and strongly recommends the continued operation of the INTEGRAL mission as detailed in the extension request. The IUG emphasises the very high-quality and unique science output, the strong potential of discoveries from future observations, the continued interest by the scientific community in the INTEGRAL mission through competitive AOs, the success of the INTEGRAL Key Programmes, and the synergies with existing and future space missions and ground based observatories. The Users Group stresses that the scientific performances and observation efficiency are retained, after the implementation of operational cost saving measures, making XMM-Newton and INTEGRAL a combined top priority for the ESA Science programme.

2 - Spacecraft, Payload and Ground Segment Status

The status of the satellite, instruments and ground segment all remain excellent. The spacecraft is being operated on prime chains throughout. No significant change in performance is expected during the requested confirmation or extension intervals. There are sufficient on-board consumables to operate well beyond the end of the extension request; the lifetime limiting consumable is fuel, which is sufficient to around 2023 at current usage rates.

The orbit continues to evolve towards higher perigee altitudes again. The minimum perigee altitude of 2750 km occurred in October 2011. This altitude will increase to 4500 km by the end of 2012 and to 10,000 km by the fall of 2015. As predicted, the lower perigee altitude has resulted in an increased proton radiation dose since around early 2011. The only impacts have been a moderate increase in the solar arrays' degradation rate and a higher number of suspect pixels in the star-trackers. Neither of these is affecting science operations and this is expected to be the case during the confirmation and extension intervals. Due to the perigee height evolution the radiation environment will be less harsh throughout this time range. Solar activity is increasing as we approach the next solar maximum (predicted for 2013) and the anti-correlated particle background rate is decreasing accordingly, reducing the pressure on telemetry usage and improving the relative signal of observed sources.

SPI has not lost any further Ge detectors since 2010[1]. As a risk mitigation measure, the detector high voltages have been reduced with minimal effect on the scientific performance. The performance of the SPI cryocoolers remains nominal and 19 annealing cycles have been successfully executed, so maintaining the excellent SPI energy resolution. For IBIS only ~0.5% additional pixels have been lost since 2010 and the total (4.4% for ISGRI and 1.3% for PICsIT) remains very low.

Due to the lower background, both JEM-X units have been operated simultaneously since October 2010. This is expected to continue in the future. The degradation in effective area is around 1% per year, lower than previously anticipated. The OMC shows no signs of degradation with a stable flat-field calibration and negligible dark current.

The INTEGRAL Ground Segment continues to operate smoothly with an unchanged prognosis during the confirmation and extension intervals. The Mission Control System at the MOC is currently being upgraded to ensure reliability and robustness to 2016.

[1] 4 out of 19 Ge detectors failed for unknown reasons in 2003, 2004, 2009 & 2010, respectively