INTEGRAL's final AO: Capabilities and Science Highlights

In light of the last Announcement of Opportunity (AO) for the INTEGRAL mission, this brochure targets all astronomers to trigger reflections of *new* science cases that could be addressed before the mission stops operating, thus those *not* already done or currently being pursued by the high-energy astronomy community. The science highlights selected for this purpose are not intended as a review of all scientific achievements, not even to cover all achievements reported as outreach articles.

As reported in a Press release about Auroral Emission, INTEGRAL can do much more than its core activities to study high-energy black holes, supernovae or neutron stars.

This brochure provides generic capabilities, followed by some *selected* examples focusing on those capabilities that may serve *new* science topics, especially outside the core scientific activities of INTEGRAL such as the INTEGRAL Burst Alert System (IBAS).

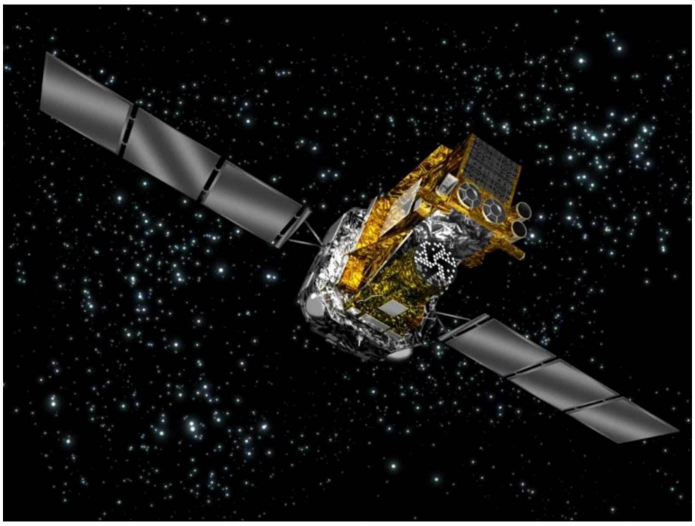
***INTEGRAL is** a multi-instrument (simultaneous) Gamma+X-ray+V-band mission with an exceptionally large field of view (including sensitivity of almost the entire sky), flying in a highly elliptical orbit allowing long uninterrupted observations.*

*Some of the most unique **capabilities** include long continuous observations, monitoring large-fields, measurements of important radioactive decay lines and 511keV annihilation line, and gamma ray polarization.*

*INTEGRAL has made many important **discoveries** such as directly establishing that Supernovae Ia are powered by exploding white dwarfs, direct (model-independent) measurements of stellar ages, or identification of phenomena of previously uncertain origins such as gamma ray bursts, gravitational wave events, fast radio bursts, or the origin of cosmic radiation.*

In a nutshell, the most important capabilities making INTEGRAL still after > 20 years a competitive mission are:

- High spectral resolution above 100keV: Only current mission measuring gamma-ray lines probing nuclear/isotopic decays, electron/positron annihilation
- Large Field of view – many sources covered simultaneously, including emission line maps!
- Long continuous observations with high observing efficiency
- The shields around SPI and IBIS provide access to the whole sky
- Unique ability to measure polarization



A. Quick Glance of Your last Opportunities

- **Capability of measuring nuclear decay lines and the 511keV annihilation line** facilitated important results such as the ultimate proof of SN Ia being powered by an exploding white dwarf, model-independent age determination of stars from isotopic decays, the energy source of Supernova remnants or the origin of cosmic rays.
  - ⇨ *Can your research benefit from nuclear line measurements or positron measurements?*
- **Large field of view** Enabled identification of first electromagnetic counterpart of a GW event, map out the spiral arms of our Galaxy etc.
  - ⇨ *High discovery potential in the archives for your favourite sources to already be well covered by INTEGRAL.*
- **Long continuous observations** enabled potent timing analysis, e.g., of the 20-30year recurrent bursting black hole V404 Cyg. Simultaneous gamma+X-ray+optical continuous light curves allow correlation studies between these bands.
  - ⇨ *Does your research involve variability of minutes/hours? Low-Earth orbit missions Swift, NuSTAR, or AstroSat plus ground-based observatories are blind to these time scales.*
  - ⇨ *INTEGRAL proposals can be driven by the large-field (several degrees!) JEM-X or the V-band monitor OMC*
- **The spectral range around 100keV and above** allowed highly obscured objects to be studied, e.g., discovering highly obscured AGN to be brighter at high energies than unobscured AGN.
  - ⇨ *Objects obscured at low energies could be good INTEGRAL targets*
- **A vibrant, experienced, and competent INTEGRAL community**
  - ⇨ *If you are a newcomer, your INTEGRAL colleagues could be a powerful source of help, e.g., you could invite them as co-I to your INTEGRAL proposal to support with feasibility, observation strategy, and later data analysis.*

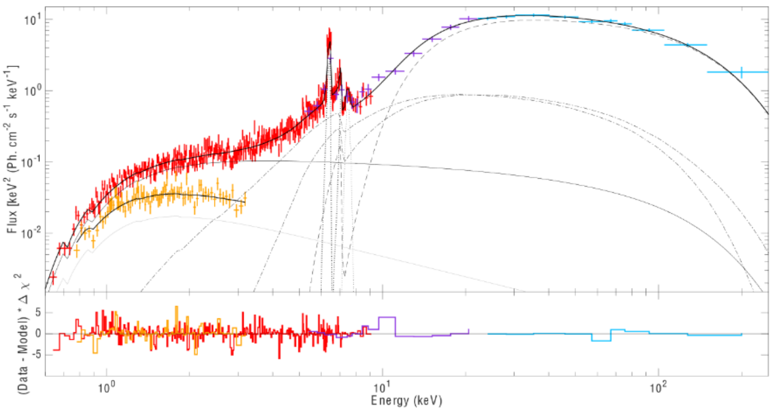


Fig.2 of Motta et al. (2017) demonstrates the spectral capability of INTEGRAL: The outbursting stellar-mass black hole binary V404 Cyg was observed with Swift XRT (red and orange: without and with obscuration, respectively) and INTEGRAL JEM-X (purple) plus IBIS/ISGRI (light blue). The hard tail is not affected by obscuration and poses important constraints on the global understanding of the complex geometry hosting emission, absorption, and scattering.

In this case rather atypical behaviour is seen, rather reminiscent of an obscured/absorbed active galactic nucleus (AGN) where the low-flux states might not (solely) be related to a decrease in the intrinsic luminosity, but could instead be caused by an almost complete obscuration of the inner accretion flow.

B. Generic Capabilities

- **Large field of view** (depending on instrument: up to 29° x 29°)
  - Observations of many sources simultaneously
  - Serendipitous discovery of transients with localisation, spectra, light curves, etc

⇨ It is likely that the INTEGRAL archives already contain observations of your favourite source, possibly even multiple times.

- **High scheduling efficiency and flexibility** fostering an efficient ToO programme.

  Thanks to proficient and experienced mission planning and operations teams, the schedule can be quickly adjusted to respond to important events.

- **Long (2.5 days!) *continuous* visibility** for uninterrupted observations

  Useful, e.g., to study time variability on all time scales from µs to several hours

  ⇨ not possible with low-Earth orbit (LEO) missions such as NuSTAR, Swift, or Astrosat or ground-based facilities.

- **Low background** far outside Earth's radiation belts – thanks to highly elliptical orbit and vetoing systems by:
- **All-sky** Anticoincidence shields (**ACS**) around SPI and IBIS:
  - Detection of gamma ray anomalies *anywhere* in the sky. While very limited localization, accurate time information facilitates important contributions to collaborations with other instruments, e.g., GW or neutrino detectors.
- Unique and **broad spectral range** with V-band+X-ray+γ-ray instruments operating simultaneously:
  - **Optical** instrument (OMC), V filter, 5°x5°

    Unique optical uninterrupted light curves over long periods of time (since gamma-ray observations are long) – time resolution of 3s is rare to find, even from the ground!
  - **X-ray** imager (JEM-X): while less sensitive than, e.g., XMM-Newton or NuSTAR, it has a much larger field of view (up to 13°, 3' FWHM)
  - 2 hard **X-ray/gamma**-ray instruments:
    - IBIS: Imager 25 keV - 10 MeV, composed of two detector planes
      - ISGRI: top layer, 15 keV - 1 MeV
      - PICsIT: bottom layer, 300 keV - 10 MeV
        - since middle July 2023 the timing resolution is 3.9 ms.

      Particularly useful for scans of large sky areas (e.g., Galactic Bulge). Two layers allow polarization measurements.
    - SPI: Spectral imager for gamma-ray point sources and extended regions (up to 16° with 2.5° resolution) in the 18 keV - 8 MeV range (2.2 keV FWHM resolution at 1.33 MeV).

      Used to measure important radioactive decay emission lines, especially also the 511keV electron/positron annihilation line. Also, polarization measurements are possible! Here some more info.

C. Examples of past Science Highlights

1. Definitive observational proof that SN Ia are exploding white dwarfs

News Item: INTEGRAL catches dead star exploding in a blaze of glory

The ability of the SPI imaging spectrometer to resolve emission lines in the γ-ray bands allowed for the first time to confirm that the underlying exploding object in a Supernova (SN) Ia is a white dwarf.

The nearby SN Ia SN2014J (in the nearby galaxy M82) was the first opportunity for INTEGRAL to prove its capabilities to detect the signature of radioactive nuclei characteristically being created by fusion during the thermonuclear explosion of a white dwarf star. Specifically, the carbon and oxygen found in a white dwarf is fused to radioactive nickel during the explosion. This nickel should then quickly decay into radioactive cobalt, which would itself subsequently decay, on a somewhat longer timescale, into stable iron. Around 50 days after the initial detonation, INTEGRAL detected the signature of the expected cobalt decay in exactly the quantities that models predicted.

An unexpected additional result was the detection of gamma rays from the decay of radioactive nickel just 15 days after the explosion. During the early phase of a Type Ia supernova, the explosion debris is thought to be so dense that the gamma rays from the nickel decay should be trapped inside. This surprising result demonstrated that the explosion had not begun in the heart of the white dwarf as one may naturally believe. Rather, a belt of gas from the companion star must have built up around the equator of the white dwarf, forming the observed nickel and then triggering the internal explosion that became the supernova.

INTEGRAL thus constituted an important contribution to our understanding of the evolution of the important SN Ia explosions in the sense that what has always been an assumption is now a fact!

2. Model-independent stellar ages with Aluminium dating method

News Item: Integral Helps Unravel the Tumultuous Recent History of the Solar Neighbourhood

Similarly to the ^{14}C isotope concentration of a probe being used for dating on age scales of 5000 years, the ^{26}Al line has a characteristic decay behaviour of 1 million years. ^{26}Al is produced in stars and expelled via supernovae into the interstellar medium. Early in the INTEGRAL mission, the decay rate of ^{26}Al was used to estimate that a supernova explodes roughly once every 50 years somewhere in the Milky Way. The same decay date can be explored to utilize SPI measurements of line intensity and shape of the ^{26}Al line to determine stellar ages independently of stellar evolution models.

While the spatial resolution (2.5°) is not sufficient for individual stars (unless *really* individual), INTEGRAL SPI measurements of the nearby Scorpius-Centaurus association, the closest group of young and massive stars to the Sun, provide evidence for recent ejections of matter from massive stars that took place only a few million years ago in our cosmic neighbourhood.

3. What powers long-term emission in Supernova Remnants

News Item: INTEGRAL finds titanium in supernova remnant 1987A

A supernova is a single explosion, but Supernova Remnants (SNR) such as that from SN1987A emit light for many years after the explosion. The energy source is thought to arise from radioactive decays, and INTEGRAL discovered a high dose of ^{44}Ti in SN1987A (after confirming ^{44}Ti in the SNR Cas A). Such measurements require long exposure durations, in this case 1500ks.

4. Origins of Cosmic Rays

News item: INTEGRAL deciphers diffuse signature of cosmic-ray electrons

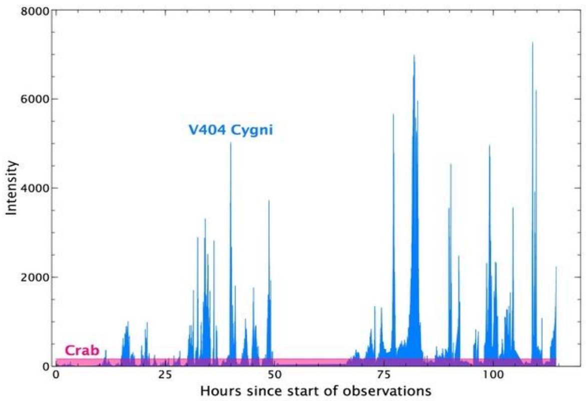
The SPI instrument allows resolving individual emission lines over a large field making it particularly suitable to study diffuse emission over large areas of the sky such as a scan of the entire Milky Way.

Such a scan revealed four mechanisms of interactions of cosmic particles:

- **Inverse Compton (IC)**: A major contribution is due to IC scattering, collisions between highly energetic cosmic electrons (or positrons) with low-energy infrared and visible photons emitted by stars, and with the ubiquitous photons of the cosmic microwave background radiation. Part of the kinetic energy of the cosmic particles are transferred to the photons, thus 'boosting' them to X- and gamma-ray wavelengths.
- **Annihilation at 511keV:** SPI also sees the annihilation of positrons with electrons and the radioactive decay of some unstable atomic nuclei. When positrons and electrons collide, they may either destroy each other immediately (photons at 511 keV) or they may create an unstable and short-lived two-particle system called positronium, which soon decays into two or more photons, producing a distinctive continuum emission spectrum up to 511 keV.
- **Radioactive Nuclei:** At energies above 1 MeV, the data also exhibit characteristic decay features of two unstable isotopes of aluminium (^{26}Al) and iron (^{60}Fe). This indicates the presence of these radioactive nuclei - the products of recent nucleosynthesis in supernova explosions - throughout the diffuse interstellar medium of the Milky Way.
- **Unresolved Soft Sources:** At low energies, below 50 keV, the superposition of many unresolved faint sources have been identified (also with data from the IBIS imager) which originates from stars with very hot coronae and cataclysmic variable stars.

5. Long, uninterrupted X-ray+γ-ray light curves of rare repeating flares

News Item: Monster Black Hole Wakes Up after 26 Years



Credit: ESA/INTEGRAL/IBIS/ISDC

The capability to take uninterrupted observations of 2.5 days enabled INTEGRAL to take this continuous light curve of the outbursting binary V404 Cygni, a binary with a stellar mass Black Hole (12 $M_\odot$) orbited by a 0.5$M_\odot$ star from where material flows towards the black hole and gathers in a disc, where it is heated up, shining brightly at optical, ultraviolet and X-ray wavelengths before spiralling into the black hole.

This system showed high activity episodes in 1938, 1956, 1989, and 2015, thus every 20-30 years. These peaks of activity are likely caused by material slowly piling up in the disc surrounding the black hole, until eventually reaching a tipping point that dramatically changes the black hole's feeding routine for a short period with intensities up to 50 times brighter than the brightest permanent gamma ray source in sky, the Crab.

Thanks to operating multiple instruments simultaneously, INTEGRAL data allow correlation studies from V band (with the OMC, see Picture of the Month November 2015) all the way to 100keV, and it was found that some flares are seen in all bands while some are delayed in the V band.

6. First electromagnetic counterpart to a gravitational wave event

New Item: INTEGRAL sees blast travelling with gravitational waves

The SPI instrument is surrounded by an Anti-Coincidence Shield (ACS) to shield the detectors against background (photons and particles) from sources outside the field-of-view. Apart from vetoing background events to reduce the background of SPI, the ACS can also be used to detect bursts outside the field of view with high sensitivity and high time resolution. While there is no spatial information, some positional information can be deduced by triangulation with other satellites. INTEGRAL catches about 20 such bursts per year.

On 17 August 2017, such a burst was detected by INTEGRAL (GRB170817A) coinciding with the famous Gravitational wave event GW170817. At the same time, NASA's Fermi telescope also detected a burst, and both independent γ-ray detections were the first time an electromagnetic counterpart was identified with a gravitational wave event. This triggered great attention in the scientific and general public. It is interesting to note that the gamma peak was detected 1.7s later than the gravitational wave event. Having seen exactly the same delay with INTEGRAL and Fermi rules out any issues with the absolute time calibration.

INTEGRAL has also made the press with an important non-detection: INTEGRAL sets limits on gamma rays from merging black holes: After a Gravitational Wave signal by LIGO, INTEGRAL's large sky coverage allowed searching the entire region identified by LIGO as possible origin of the event but *without* detecting any gamma ray source. This is consistent with the scenario of merging stellar-mass black holes where the emission is trapped within the event horizon.

7. Association of a Fast Radio Burst with a magnetar

News Item: Dead star emits never-before seen mix of radiation

Sometimes, the mysteries in one waveband can be solved by observations in other wavebands. Such a mystery have been the "Fast Radio Bursts" – until INTEGRAL came along: Fast Radio bursts were first discovered in 2007 as events pulsing brightly in radio waves for just a few milliseconds before fading away, and were only rarely seen again. No such burst has ever been observed within the Milky Way, with a known origin, nor emitting any other kind of radiation beyond the radio wave domain.

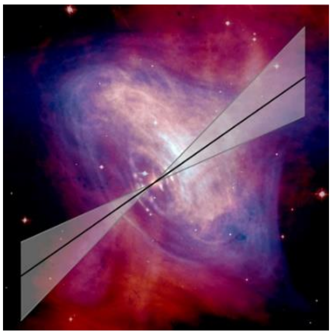
Their origin remained a problem of the radio community until the INTEGRAL Burst Alert System (BAS) quickly alerted the community of a burst from a known magnetar. Thanks to the large field of the IBIS imager, the origin of the burst could be precisely pinpointed, nailing its association with the magnetar.

Subscribing to the alerts from the INTEGRAL Burst Alert System (IBAS) can thus be beneficial, not only to the G-ray Burst (GRB) community. Instructions are given under:
https://www.isdc.unige.ch/integral/science/grb

8. Spatial resolution from gamma-ray polarization measurements

News Item: INTEGRAL detects signature of critical cosmic accelerator

The IBIS and SPI instruments are not only efficient large-field imaging and high spectral resolution instruments, but they can also be used to determine polarization.



While INTEGRAL does not have the great angular resolution (3' for JEM-X) of Chandra (1") and cannot pinpoint the origin of the strong γ-ray emission in the Crab nebula, the orientation of the polarization was found to be directly correlated with the orientation of the magnetic field where the photons are radiated. With this information, and by leveraging information from observations at other energies, INTEGRAL measurements allowed estimates of the radiating electrons that must have an energy of the order of 10^{15} eV.

9. Gravitational Lensing also works with INTEGRAL

News Item: Astronomers use cosmic gravity to create a 'black-hole-scope'

Gravitational lensing is independent of wavelength and thus works the same ways with light of all energies. Although many billions of light years away, INTEGRAL scientists used a star sitting between their target and Earth to 'zoom in' to the black hole and measure the size of the jet-emitting region to scales of 100 AU – the first time this method has ever been used with gamma rays. The method allowed INTEGRAL to 'resolve' the central jet region and get an insight into the patch of space directly surrounding a supermassive black hole known as PKS 1830-211. These observations demonstrated that the gamma rays come from the direct vicinity of the black hole itself.

10. Surprises when looking at high energies

The AGN unification model predicts that all AGN exhibit the same behaviour when observed at hard X-ray wavelengths, regardless of the different emission they might show in other bands. Depending on the orientation of the torus with respect to an observer's line of sight, the view to the galactic nucleus may be obstructed to varying degrees, thus providing a phenomenological interpretation of the observed AGN diversity. INTEGRAL observations of 165 AGN (later increased, now 436 AGN: Malizia et al. 2023) at energies between 20-250 keV revealed that the sources affected by stronger absorption at lower energies (i.e. from the infrared to the soft X-ray bands) show an excess of hard (30-60keV) emission, with respect to their less obscured counterparts. The excess emission is a signature of X-rays being reflected off neutral hydrogen gas in the dense clouds that surround the black hole and disc, possibly the same clouds responsible for absorption at lower energies.

Thanks to the sensitivity above 100keV, the large field of view and long monitoring campaigns, INTEGRAL also established a new class of Supergiant X-ray Binaries. The dense stellar wind of the OB supergiant companion in a bursting binary system obscures soft X-ray emission making this class appear to be rare, however, INTEGRAL established that this is a sizable class of objects.

But also upper limits like in the gravitational wave event GW150914 can be of high relevance as this is consistent with the scenario of merging stellar-mass black holes where the emission is trapped within the event horizon.