Science with the International Gamma-Ray Astrophysics Laboratory INTEGRAL

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Abstract.
The International Gamma-Ray Astrophysics Laboratory (INTEGRAL), to be launched in 2001, is dedicated to the fine spectroscopy (ΔE: 2 keV FWHM @ 1.3 MeV) and fine imaging (angular resolution: 12′ FWHM) of celestial gamma-ray sources in the energy range 15 keV to 10 MeV with concurrent source monitoring in the X-ray (3 - 35 keV) and optical (V, 550 nm) range. The mission is conceived as an observatory led by ESA with contributions from Russia and NASA. The INTEGRAL observatory will provide to the science community at large an unprecedented combination of imaging and spectroscopy over a wide range of gamma-ray energies. This paper summarises the key scientific goals of the mission, the current development status of the payload and spacecraft and it will give an overview of the science ground segment including the science data centre, science operations and key elements of the observing programme.

INTRODUCTION

The International Gamma-Ray Astrophysics Laboratory (INTEGRAL) is dedicated to the fine spectroscopy (ΔE: 2 keV FWHM @ 1.3 MeV) and fine imaging (angular resolution: 12′ FWHM) of celestial gamma-ray sources in the energy range 15 keV to 10 MeV. The INTEGRAL observatory will provide to the science community at large an unprecedented combination of imaging and spectroscopy over a wide range of X-ray and gamma-ray energies including optical monitoring. The mission is conceived as an observatory led by ESA with contributions from Russia and NASA and will be launched in 2001. ESA is responsible for the overall spacecraft and mission design, instrument integration into the payload module, spacecraft integrations and testing, spacecraft operations including one ground station, science operations, and distribution of scientific data. Russia will provide a PROTON launcher and launch facilities, and NASA will provide ground station support

[1] on behalf of the INTEGRAL Science Working Team.

through the Deep Space Network. The scientific instruments and the INTEGRAL Science Data Centre will be provided by large collaborations from many scientific institutes of ESA member states, USA, Russia, Czech Republic and Poland, nationally funded, and led by Principal Investigators (PI's).

SCIENTIFIC OBJECTIVES

INTEGRAL is a 15 keV - 10 MeV gamma-ray mission with concurrent source monitoring at X-rays (3 - 35 keV) and in the optical range (V, 500 - 600 nm). All instruments - co-aligned with large FOV's - cover simultaneously a very broad energy range of high energy sources (Tables 1, 2).

The scientific goals of INTEGRAL will be attained by fine spectroscopy with fine imaging and accurate positioning of celestial sources of gamma-ray emission. Fine spectroscopy over the entire energy range will permit spectral features to be uniquely identified and line profiles to be determined for physical studies of the source region. The fine imaging capability of INTEGRAL within a large field of view will permit the accurate location and hence identification of the gamma-ray emitting objects with counterparts at other wavelengths, enable extended regions to be distinguished from point sources and provide considerable serendipitous science which is very important for an observatory-class mission. In summary the scientific topics will address: (i) compact objects: *white dwarfs, neutron stars, black hole candidates, high energy transients and GRB's*; (ii) extragalactic astronomy: *galaxies and clusters, AGN, Seyferts, Blazar, cosmic diffuse background*; (iii) stellar nucleosynthesis: *hydrostatic nucleosynthesis (AGB and WR stars), explosive nucleosynthesis (Supernovae and novae)*; (iv) Galactic structure and the Galactic Centre: *cloud complex regions, mapping of the continuum and line emission, ISM, cosmic-ray distribution*; (v) particle processes and acceleration: *transrelativisic pair plasms, beams, jets*, (vi) identification of high energy sources: *unidentified gamma-ray objects as a class*; PLUS: (vii) unexpected discoveries.

Recent new results from high-energy observations of millisecond radio pulsars increase substantially the expectation that INTEGRAL can also contribute significantly to the study of rotation powered neutron stars. To date, three millisecond pulsars have been detected at energies above 2 keV with very hard non-thermal pulsed emission, namely PSR B1821-24 (ASCA, [5]; RXTE, [4]), PSR B1937+21 (ASCA, [6]) and PSR J0218+4232 (ROSAT, [2]; BeppoSAX, [3]). The pulsed emissions have power-law spectral shapes, with indexes between $\sim$ -0.6 and $\sim$ -1.2, and exhibit X-ray pulses with intrinsic widths $\leq$ 100 μsec. Surprisingly, for PSR J0218+4232 convincing evidence has been reported in this meeting [1] for detection in the EGRET data of pulsed high-energy γ-ray emission between 100 MeV and 1 GeV. Extrapolations of the pulsed spectra measured between 1 and 10 keV into the INTEGRAL energy range, as well as interpolation between the spectra measured for PSR J0218+4232 below 10 keV and above 100 MeV, demonstrate that INTEGRAL will be capable to bridge the intermediate gap, most importantly the energy interval between 50 keV and 1 MeV. These studies will provide important parameters for modelling the production of pulsed high-energy emission in the magnetosphere of (millisecond) pulsars. In addition, we cannot exclude that part of the unidentified high-energy gamma-ray sources are millisecond pulsars. INTEGRAL might also shed some light on this problem.

SCIENTIFIC PAYLOAD

TABLE 1. INTEGRAL science and payload complementarity

Instrument	Energy range	Main purpose
Spectrometer SPI	20 keV - 8 MeV	Fine spectroscopy of narrow lines Study diffuse emission on >deg scale
Imager IBIS	15 keV - 10 MeV	Accurate point source imaging Broad line spectroscopy and continuum
X-ray Monitor JEM-X	3 - 35 keV	Source identification Monitoring @ X-rays
Optical Monitor OMC	500 - 600 nm	Optical monitoring of high energy sources

The INTEGRAL payload consists of two main gamma-ray instruments: Spectrometer SPI and Imager IBIS, and of two monitor instruments, the X-ray Monitor JEM-X and the Optical Monitoring Camera OMC. The design of the INTEGRAL instruments is largely driven by the scientific requirement to establish a payload of scientific complementarity. As shown in Table 1, the payload does meet this goal.

Each of the main gamma-ray instruments, SPI and IBIS, has both spectral and angular resolution, but they are differently optimised in order to complement each other and to achieve overall excellent performance. The two monitor instruments (JEM-X and OMC) will provide complementary observations of high energy sources at X-ray and optical energy bands. An overview of the INTEGRAL payload is given below, detailed descriptions can be found in the various instrument papers presented at this symposium. Also part of the payload is a small particle radiation monitor, which continuously measures the particle environment of the spacecraft. Therefore it is possible to provide essential information to the payload in case high particle background (radiation belts, solar flares) is being encountered. This information is used to decide on switch - off and switch - on of instrument high voltages and to provide actual background information for sensitivity estimates.

Spectrometer SPI

The Spectrometer SPI (Table 2) will perform spectral analysis of gamma-ray point sources and extended regions with an unprecedented energy resolution of 2 keV (FWHM) at 1.3 MeV. This will be accomplished using an array of 19 hexagonal high purity Germanium detectors cooled by two pairs of Stirling Coolers to 85 K. The total detection area is 500 cm^2. A hexagonal coded aperture mask is located 1.7 m above the detection plane in order to image large regions of the sky (fully coded field of view = 16°) with an angular resolution of 2°. In order to reduce background radiation, the detector assembly is shielded by an active BGO veto system which extends around the bottom and side of the detector almost completely up to the coded mask. A plastic veto between mask and upper veto shield ring further reduces background events.

Imager IBIS

The Imager IBIS (Table 2) provides powerful diagnostic capabilities of fine imaging (12′ FWHM), source identification and spectral sensitivity to both continuum and broad lines over a broad (15 keV - 10 MeV) energy range. The energy resolution is 7 keV @ 0.1 MeV and 60 keV @ 1 MeV. A tungsten coded aperture mask (located at 3.2 m above the detection plane) is optimised for high angular resolution imaging. Sources ($> 10\sigma$) can be located to $< 60''$. As diffraction is negligible at gamma-ray wavelengths, the angular resolution obtainable with a coded mask telescope is limited by the spatial resolution of the detector array. The IBIS design takes advantage of this by utilising a detector with a large number of spatially resolved pixels, implemented as physically distinct elements. The detector uses two planes, a front layer (2600 cm^2) of CdTe pixels, each (4x4x2) mm, and a second one (3100 cm^2) of CsI pixels, each (9x9x30) mm. The division into two layers allows the paths of the photons to be tracked in 3D, as they scatter and interact with more than one element. The aperture is restricted by a thin passive shield. The detector array is shielded from the sides and below by an active BGO veto.

X-Ray Monitor JEM-X

The Joint European X-Ray Monitor JEM-X (Table 2) supplements the main INTEGRAL instruments (Spectrometer SPI and Imager IBIS) and plays a crucial role in the detection and identification of the gamma-ray sources and in the analysis and scientific interpretation of INTEGRAL gamma-ray data. JEM-X will make observations simultaneously with the main gamma-ray instruments and provides images with 3′ angular resolution in the 3 - 35 keV prime energy band. The photon detection system consists of two identical high pressure imaging microstrip gas chambers (Xenon at 5 bar) each viewing the sky through a coded aperture mask (4.8° fully coded FOV), located at a distance of 3.2 m above the detection plane. The total detection area is 1000 cm^2.

Optical Monitoring Camera OMC

The Optical Monitoring Camera OMC (Table 2) consists of a passively cooled CCD in the focal plane of a 50 mm lens. The CCD (1024 x 2048 pixels) uses one section (1024 x 1024 pixels) for imaging, the other one for frame transfer before readout. The FOV is $5^\circ \times 5^\circ$ with a pixel size of $17.6''$. The OMC will observe the optical emission from the prime targets of the INTEGRAL main gamma-ray instruments with the support of the X-Ray Monitor JEM-X. Variability patterns on timescales of 1 s and longer, up to months and years will be monitored. The limiting magnitude of 19.7^{m_v} (3σ, 10^3 s), corresponds to $\sim$40 photons $cm^{-2}s^{-1}keV^{-1}$ (@ 2.2 eV) in the V-band. Multi-wavelength observations are particularly important in high-energy astrophysics where variability is typically rapid. The wide band observing opportunity offered by INTEGRAL is of unique importance in providing for the first

TABLE 2. Key parameters of the INTEGRAL scientific payload.

	SPI	IBIS	JEM-X	OMC
Energy range	20 keV - 8 MeV	15 keV - 10 MeV	3 keV - 35 keV	500 nm - 600 nm
Detector area (cm^2)	500	2600 (CdTe) 3100 (CsI)	1000 (2 units each 500)	CCD (2048×1024 pxl)
Spectral resolution (FWHM, keV)	2 @ 1.3 MeV	7 @ 100 keV 60 @ 1 MeV	1.5 @ 10 keV	–
Field of view (fully coded)	16°	9° x 9°	4.8°	5.0° x 5.0°
Angular resolution	2° FWHM	12′ FWHM	3′ FWHM	17.6″/pixel
Typical source location	20′	< 1′	< 20″	< 8″
Continuum sensitivity[a]	7×10^{-8} @ 1 MeV	4×10^{-7} @ 100 keV	1×10^{-5} @ 6 keV	19.7^{m_v} (3σ, 10^3 s)
Line sensitivity[b]	5×10^{-6} @ 1 MeV	1×10^{-5} @ 100 keV	2×10^{-5} @ 6 keV	–
Timing accuracy (3σ)	100 μs	67μs – 1000 s	128 μs	> 1s
Mass (kg)	1309	628	65	17
Power (W)	373	275	55	18
Data rate (kbps)	20 (avge)	57 (avge)	7	2

[a] Units are (ph cm^{-2} s^{-1} keV^{-1}) for 3σ detection in 10^6 s.
[b] Units are (ph cm^{-2} s^{-1}) for 3σ detection in 10^6 s.

time simultaneous observations over seven orders of magnitude in photon energy for some of the most energetic objects in the Universe.

MISSION SCENARIO

The INTEGRAL spacecraft consists of a service module (commonly designed with the service module of the ESA XMM mission) containing all spacecraft subsystems, and a payload module containing the scientific instruments. During summer 1998, the service module and the payload have succesfully completed the structural and thermal test (STM) programme and the electrical test (EM) programme has been completed in August 1999.

INTEGRAL (with a payload mass of 2019 kg and a total launch mass of ~4000 kg) will be launched in 2001 by a Russian PROTON launcher into a highly eccentric orbit with high perigee in order to provide long periods of uninterrupted observation with nearly constant background and away from trapped radiation. The parameters for the orbit are: period 72 hours, inclination 51.6°, initial perigee height 10 000 km, initial apogee height 153 000 km. The particle background radiation affects the performance of high-energy detectors, and scientific observations will therefore be carried out while the spacecraft is above an altitude of nominally 40 000 km. The particle background of the local spacecraft environment will be continuously measured by the on-board radiation monitor: this device allows the optimisation of the observing time before or after radiation belt passages and solar flare events,

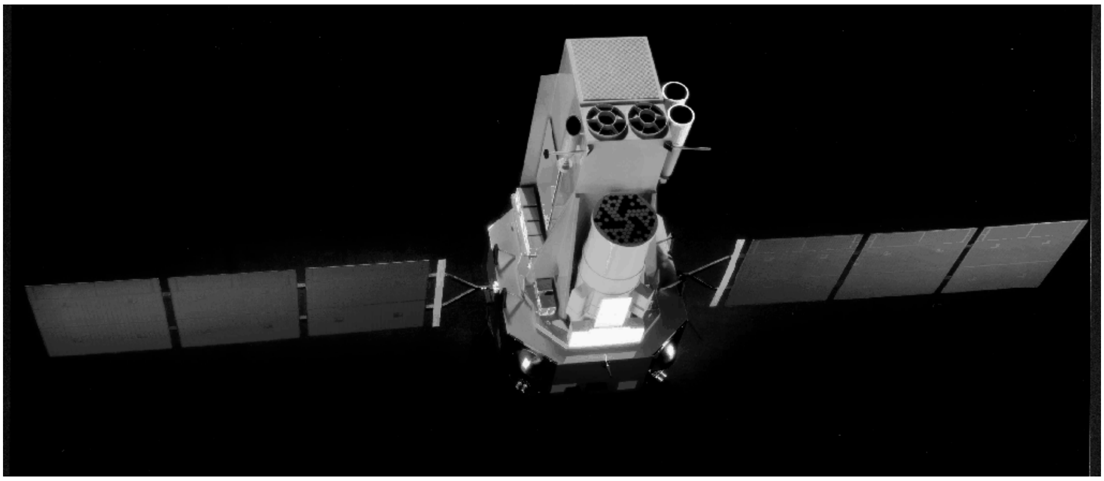

FIGURE 1. The INTEGRAL spacecraft. The cylindrically shaped SPI is next to the larger rectangular payload module (PLM) structure housing the IBIS and JEM-X detectors inside. The top of the PLM carries the coded mask for IBIS (squared) and two coded masks for the two redundant JEM-X detectors. The OMC and two star trackers are located at the top of the PLM. The size of the spacecraft (w/o solar arrays) is ~ 4x4x6 m (lxwxh).

and provides essential information about the actual background. Data from the onboard radiation monitor will be routinely checked to verify and possibly update the nominal altitude above which scientific observations will be performed. A nominal altitude of 40 000 km implies that 90% of the time spent on the orbit can be used for scientific observations. However, a number of in-orbit activities have an influence on the net amount of orbit time (e.g. slews, eclipses, resctrictive spacecraft operations, instrument calibrations) such that the average observation efficency becomes ~85% per year. The real-time scientific data rate (including instrument housekeeping) is 86 kbps.

The spacecraft employs fixed solar arrays: this means, that the target pointing of the spacecraft (at any point in time) will remain outside an avoidance cone around the sun and anti-sun. This leads to a minimum angle between any celestial source and the sun/anti-sun of 50° during the nominal mission life (2 years) outside eclipse seasons and 60° during extended mission life (year 3+). During eclipse seasons of the nominal mission (few weeks per year) 60° will be applied.

Because of imaging deconvolution requirements by SPI, the spacecraft will routinely, during nominal operations, perform a series of off-source pointing manouevres, known as "dithering". These dithering patterns consist of sets of different pointings at sky positions around the nominal target position (at the centre). The dithering points are separated by 2°. The exposure time per point is 30 minutes. Two dither patterns will be employed: a 7 point hexagone and a 5×5 point raster, both centred on the target position. If required by observers, dithering can be disabled.

GROUND SEGMENT AND SCIENCE OPERATIONS

The ground segment (Figure 2) consists of three major elements, ESA's Mission Operations Centre (MOC), the INTEGRAL Science Operations Centre (ISOC), and the INTEGRAL Science Data Centre (ISDC) plus two ground stations (ESA, NASA). MOC will implement the observation plan received from the ISOC within the spacecraft system constraints into an operational command sequence.

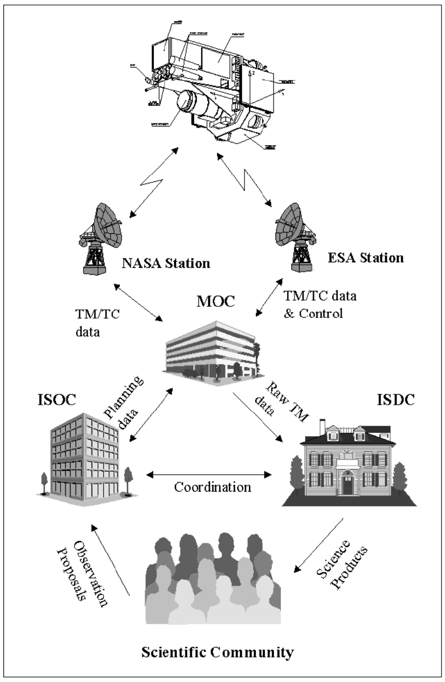

FIGURE 2. The INTEGRAL ground segment.

In addition, MOC will perform all classical spacecraft operations, real-time contacts with spacecraft and payload, maintenance tasks and anomaly checks (including payload critical health and safety). MOC will determine the spacecraft attitude and orbit, and will provide raw science data to the ISDC.

The ISOC, provided by ESA and located at ESTEC, will issue the AO for observing time and will handle the incoming proposals which will be processed into an optimised observation plan which consists of a timeline of target pointings plus the corresponding instrument configuration. This observation plan will then be forwarded to MOC to be uplinked to the spacecraft. Furthermore, the ISOC will validate any changes made to parameters describing the on-board instrument configuration and it will keep a copy of the scientific archive produced at the ISDC. Finally, the ESA Project Scientist at the ISOC will decide on the generation of TOO alerts (Target of Opportunity) in order to update and reschedule the observing programme.

The ISDC, located in Versoix, Switzerland, will receive the complete raw science telemetry plus the relevant ancillary spacecraft data from the MOC. Science data will be processed, taking into account the instrument characteristics, and raw data will be converted into physical units. Using incoming science and housekeeping information, the ISDC will routinely monitor the instrument science performance and conduct a quick-look science analysis. Most of the Targets of Opportunity (TOO) showing up during the lifetime of INTEGRAL will be detected at the ISDC during the routine scrutiny of the data and will be reported to ISOC. Scientific data products obtained by standard analysis tools will be distributed to the observer and archived for later use by the science community. INTEGRAL will be an observatory-type mission with a nominal lifetime of 2 years, an extension up to 5 years is technically possible. Most of the observing time (65% during year 1, 70% (year 2), 75% (year 3+)) will be awarded to the scientific community at large as the General Programme. Typical observations will last from 10's of minutes up to two weeks. Proposals, following a standard AO process, will be selected on their scientific merit only by a single Time Allocation Committee. These selected observations are the base of the General Programme. The first call for observation proposals is scheduled for release during first half of 2000. In principle, observers will receive data from all co-aligned and simultaneously operating instruments onboard INTEGRAL. The remaining fraction of the observing time will be reserved, as guaranteed time, for the INTEGRAL Science Working Team for its contributions to the programme. This fraction, the Core Programme, will be devoted to: (i) a Galactic Plane Survey, (ii) a deep exposure of the central radian of the Galaxy, and (iii) pointed observations of selected regions/targets including TOO follow up observations. The current status of the Core Programme is described in detail by [7]. The full details of the Core Programme will be made available at the issue of the first AO. In accordance with ESA's policy on data rights, all scientific data will be made available to the scientific community at large one year after they have been released to the observer. This guarantees the use of the scientific data for different investigations beyond the aim of a single proposal.

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