INTEGRAL: THE CURRENT STATUS

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ABSTRACT 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 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 energies. Most of the observing time will be open to the scientific community. 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 data centre, science operations and the key elements of the observing programme.

KEYWORDS: INTEGRAL; Gamma-ray astronomy; nuclear astrophysics; compact objects; coded mask imaging; spectroscopy; observatory; ESA

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

2. 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, (ii) stellar nucleosynthesis, (iii) high energy transients, (iv) mapping of diffuse continuum and line emission, (v) the galactic Centre, (vi) particle processes and acceleration, (vii) transrelativistic pair plasmas (viii) nearby galaxies, clusters of galaxies, AGN, cosmic diffuse background, (ix) identification of high energy sources, (x) compilation of unidentified gamma-ray objects as a class, PLUS: (xi) unexpected discoveries.

In particular our present knowledge of the galactic Centre region, a classical target for high energy astrophysics, is at these energies largely based on the results on (mostly variable) point sources detected in hard X-rays/low energy gamma-rays by the GRANAT instruments SIGMA (Vargas et al. 1997) and ART - P (Pavlinsky et al. 1994), as well as the results on diffuse galactic emission as measured by the CGRO instruments COMPTEL at 1.8 MeV of Al^{26} (Diehl et al. 1995) and OSSE at 511 keV (Purcell et al. 1997). The following (incomplete) list shows what can be studied in great detail with INTEGRAL:

- map diffuse 511 keV and 1.8 MeV emission on large angular scale
- measure the spectrum of the diffuse Galactic continuum emission
- image known sources, identify new point sources, companions of compact sources and hot spots from diffuse mapping in the G.C. region with high accuracy
- determine the point source contribution to the observed 511 keV flux
- study the continuum characteristics of an ensemble of point sources (spectral shape of neutron stars vs black hole candidates)
- perform spectroscopic studies of individual point sources: narrow lines (cyclotron and nuclear lines), broad lines (511 keV features including backscattering lines), line shifts (gravitational redshift ?), line shapes and line profiles
- perform continuum and line studies of "hot spots" identified in diffuse maps, i.e. the cosmic ray/dust ratio and cosmic ray/gas ratio in case of narrow and broad lines, respectively, with line profile analysis and isotope determination
- timing, variability (QPO's) and polarisation analysis of compact sources

3. SCIENTIFIC PAYLOAD

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

Table 1: INTEGRAL science and payload complementarity

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 workshop. 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.

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

Table 2: Key parameters of the INTEGRAL scientific payload. (1) Units of sensitivities are (ph cm^{-2} s^{-1} keV^{-1}) for continuum and (ph cm^{-2} s^{-1}) for lines.

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

FIGURE 1. The structural & thermal model of INTEGRAL during testing in ESTEC (Summer 98). The cylindrically shaped SPI is next to the larger rectangular payload module (PLM) structure housing the IBIS and JEM-X detectors inside. The rectangular (golden) side of the PLM covers the IBIS and JEM-X coded masks. Below the PLM are two star trackers, above the OMC. The black octagonal structure to the left is the service module. Solar arrays are not shown.

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

4. 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 1997, the service module and the payload have succesfully completed the structural and thermal test (STM, Figure 1) programme and the electrical test (EM) programme is well underway. Further details on the current spacecraft design can be found in Carli et al. 1999).

INTEGRAL (with a payload mass of 2019 kg and a total launch mass of $\sim$4000 kg) will be launched in April 2001 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 baseline is to launch INTEGRAL with a Russian PROTON. ESA and the Russian Space Agency have signed an arrangement in November 1997 formally securing the launcher for the mission. The parameters for the orbit (see Carli et al. (1999) for further details) are: period 72 hours, inclination 51.6°, initial perigee height 10 000 km, initial apogee height 153 000 km. This orbit is a modification from the previous one (e.g. Winkler 1997) in order to simplify both launcher operations and ground coverage, and for scientific reasons, to maximize the time the spacecraft is spending above $\sim$40 000 to 60 000 km based on recent analysis (Vargas 1998) of the radiation background observed by SIGMA/GRANAT at those high altitudes: the particle background radiation affects the performance of high-energy detectors, and scientific observations will be carried out while the spacecraft is above an altitude of nominally 40 000 km. However, 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, 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 provided by PROTON 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) has been recently increased by $\sim$30% to 86 kbps, an increase basically driven by scientific timing requirements of the IBIS instrument.

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. This leads to a minimum angle between any celestial source and the sun of 50° during the nominal mission life (2 years) outside eclipse seasons and 60° during extended mission life (year 3+). During eclipse seasons (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 20 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.

5. GROUND SEGMENT

The ground segment consists of two major elements, the Operations Ground Segment (OGS) and the Science Ground Segment (SGS): The OGS, consisting of the ESA and NASA ground stations and ESA's Mission Operations Centre (MOC) at ESOC will implement the observation plan received from the INTEGRAL Science Operations Centre (ISOC) within the spacecraft system constraints into an operational command sequence (Schmidt et al. 1999). In addition, the OGS will perform all classical spacecraft operations, real-time contacts with spacecraft and payload, maintenance tasks and anomaly checks (i.e. including payload critical health and safety). MOC will determine the spacecraft attitude and orbit, and will provide raw science data to the SGS.

The SGS itself consists of two centres, the INTEGRAL Science Operations Centre (ISOC) and the INTEGRAL Science Data Centre (ISDC). The ISOC (Barr et al. 1999), provided by ESA and located at ESTEC, will issue the AO for observing time and handle the incoming proposals. Accepted observation proposals will then be processed at ISOC 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 (Courvoisier et al., 1999), located in Versoix, Switzerland, will receive the complete raw science telemetry plus the relevant ancillary spacecraft data from the OGS/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.

At the time of writing, the software development for the ground segment is proceeding according to schedule. Many elements of the software architecture are completing the architectural design phase or are commencing detailed design phase.

6. OBSERVING PROGRAMME

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 at the end of 1999. In principle, observers will receive data from all co-aligned and simultaneously operating instruments onboard INTEGRAL. The remaining fraction of the observing time (i.e. 35% (year 1), 30% (year 2), 25% (year 3+)) 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 Winkler et al. (1999). 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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