The INTEGRAL mission

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ABSTRACT

INTEGRAL is ESA's next gamma-ray astronomy mission and is set for launch on 2002 October 17, from Baikonur on a Russian Proton rocket into a 72 hour orbit with an apogee of 150,000 km and a perigee of 10,000 km. INTEGRAL will study some of the most extreme objects in the Universe such as black holes, and neutron stars as well as the mysterious gamma-ray bursts, the most energetic explosions known. The payload consists of two gamma-ray telescopes – SPI, or Spectrometer on INTEGRAL, which will measure gamma-ray energies very precisely and IBIS, or Imager on Board the INTEGRAL Satellite, which will provide very fine images. The sensitivity of INTEGRAL is extended to lower energies by X-ray and optical monitors - the Joint European X-ray Monitor (JEM-X) and the Optical Monitoring Camera (OMC). The improved imaging and spectral capabilities of INTEGRAL compared to previous gamma-ray missions, as well as the broadband monitoring will provide the scientific community with an unprecedented opportunity to investigate the nature of the extreme Universe.

Keywords: INTEGRAL, gamma-ray astronomy

1. INTRODUCTION

Observations with INTEGRAL will reveal a violent, highly variable, Universe where intense new sources can suddenly appear, emit almost unbelievable amounts of energy and then disappear, sometimes never to be seen again. INTEGRAL's task will be to collect gamma-rays, the most energetic radiation that comes from space, to allow astronomers to study such bizarre objects as black holes, neutron stars – objects so dense that a teaspoon full would weigh millions tonnes here on Earth – and the mysterious gamma-ray bursts which may be signalling the explosive deaths of massive stars. All of these objects release vast amounts of energy, much of it in the form of gamma-rays. INTEGRAL, together with ESA's XMM-Newton X-ray observatory launched in 1999, is set to substantially improve our understanding of the violent Universe.

Observing gamma-rays is difficult because they easily pass straight through the mirrors and cameras of normal telescopes. Instead, INTEGRAL will use two specially designed gamma-ray telescopes. SPI or Spectrometer on INTEGRAL, will measure their energy very precisely, while IBIS, or Imager on Board the INTEGRAL Satellite, will provide very fine images. Together with the Joint European X-ray Monitor (JEM-X) and the Optical Monitoring Camera (OMC), all the INTEGRAL instruments will observe the same region of sky at the same time. It will be a prime task of the astronomers who are going to use INTEGRAL to combine the measurements made with the different instruments in the best possible way to allow the overall properties of the gamma-ray sources to be studied.

INTEGRAL will continue the strong European tradition in gamma-ray astronomy that started with ESA's COS-B satellite in 1975. This was followed by the Russian-French mission GRANAT (1989-1998) and NASA's Compton Gamma-ray Observatory (1991-2000) to which European institutes contributed. The international High Energy Transient Explorer satellite (HETE-2) was launched in 2000 and includes a French gamma-ray telescope and X-ray detectors. Soon astronomers will have INTEGRAL, the most sensitive gamma-ray observatory ever.

2. INTEGRAL SCIENCE OBJECTIVES

2.1 SUPER-DENSE STARS

When a massive star explodes, not all the material is ejected into space. Some of it can collapse into an extremely compact object known as a neutron star. A neutron star is only the size of a city, but may contain as much material as two or three stars like the Sun. It is no wonder that neutron stars are incredibly dense; a teaspoon full of neutron star stuff would weigh millions of tonnes here on Earth! Some neutron stars have incredibly strong magnetic fields due to the original star's magnetic field being "trapped" and concentrated during the collapse. As they spin these magnetic neutron stars may emit strong radio pulses and are known as "pulsars". If such magnetic neutron stars are located in binary systems and the companion star is close enough to transfer material onto the neutron star they are known as "accreting X-ray pulsars". As this material falls onto the neutron star it becomes extremely hot and emits large numbers of X- and gamma-rays. These binaries can therefore provide a natural laboratory by which to study the interaction of ultra-hot material with ultra-strong magnetic fields. Such conditions are simply too extreme to be reproduced in laboratories on Earth. INTEGRAL will capture images of the high-energy emission from these objects with unprecedented detail, allowing astronomers a clearer look than ever before.

However, neutron stars are not the most bizarre objects that INTEGRAL will observe. Neutron stars containing more than about three times the Sun's mass become unstable and collapse even further becoming a black hole. These are perhaps the strangest objects in the Universe because nothing, not even light, can escape from inside the black hole. So the presence of a black hole can only be inferred by its effect on any surrounding objects.

2.2 UNDERSTANDING BLACK HOLES

Understanding the nature and properties of black holes is one of the key scientific objectives of INTEGRAL. The masses of black holes are thought to range from a few times that of the Sun to many millions of times that of the Sun. Scientists believe that such giant black holes lie at the centre of many galaxies, including our own Milky Way. When there is material close enough to be drawn into the hole by the enormous gravitational field it will emit phenomenal amounts of energy before disappearing into the black hole. Such systems are known as Active Galactic Nuclei, or AGN. It is believed that there is a two million solar mass black hole present in the heart of our Galaxy. It is not currently active, although it may have been a few hundred years in the past.

However, from radio and optical observations it is known that the heart of our Galaxy is still a site of violent activity, perhaps resulting from past activity. At gamma-ray energies this behaviour is brought clearly into view. Arching up from the centre of the Galaxy is an enormous cloud of anti-matter that is glowing brightly in gamma-rays, created by the annihilation of matter and anti-matter. INTEGRAL will investigate the nature of this emission with unprecedented sensitivity and so help us to understand the nature of the giant black hole at the centre of our Galaxy.

INTEGRAL will study yet another class of black holes. These are black hole systems with masses just a few times that of the Sun. If these black holes are in binary systems then the companion star can provide material that falls into the black hole. As this happens the material gets extremely hot and emits X- and gamma-rays. Thus, the presence of intense X- and gamma-ray emission from a binary system may indicate the presence of a black hole, hidden from direct view. Many of systems are "transients", meaning that they do not give off gamma-rays most of the time and usually remain hidden amongst the billions of stars in our Galaxy. The study of these transient outbursts is of prime scientific importance and most weeks INTEGRAL will devote time to a search for new transient sources. Whenever a new transient is discovered, the INTEGRAL scientists will alert the worldwide astronomical community so that observations with other facilities and satellites can be organised. INTEGRAL will be able to address many outstanding problems in black hole research, such as whether there are distinctive spectral signatures that can be used to discriminate between black holes and their cousins the super-dense, neutron stars.

2.3 PROBING THE MYSTERIOUS BURSTS

Around once a day, astronomical satellites detect sudden bursts of gamma-rays coming from anywhere in the Universe. These bursts can be briefly the brightest objects in the gamma-ray sky, but are never seen to repeat. For many years astronomers had no idea how far away these explosions were. This changed in 1997 when the Italian-Dutch satellite BeppoSAX provided accurate burst positions quickly enough to allow the still glowing debris to be detected in optical, radio and X-ray telescopes. These observations showed that gamma-ray bursts occur at huge distances, similar to those of the farthest galaxies, and therefore that they are incredibly energetic, briefly glowing brighter than a billion stars.

Astronomers believe that this colossal amount of energy could be released when a massive star catastrophically collapses in on itself leaving a black hole in a massive explosion known as a "hypernova". Not all gamma-ray bursts may have the same origin, and some astronomers believe that colliding neutron stars or black holes may be responsible for some of the bursts. More observations of the glowing debris are desperately needed in order to understand what is really happening. However, now that BeppoSAX is no longer operating, it is much harder to find suitable Gamma-ray bursts to investigate. The large fields of view of the INTEGRAL gamma-ray instruments will allow the chance detection of a few gamma-ray burst per month, a similar rate to that provided by BeppoSAX. In addition, INTEGRAL itself will be able to search the glowing debris for evidence of the atoms created.

2.4 CREATING THE ATOMS

Scientists are confident that most of the elements that we are made from were once in the hearts of stars. From there they were released into space at the end of a star's life, often in a violent explosion called a supernova. The precise nature of how this happens remains elusive and is one of the top goals of INTEGRAL.

The abundance of the elements can be measured directly on Earth and in meteorites. In addition astronomical observations can reveal the composition of stars, galaxies, and the interstellar medium. Scientists believe that the very early Universe consisted almost entirely of hydrogen and helium, the simplest elements. All the other elements were created inside stars or in supernova explosions. Most stars, including the Sun generate energy by changing hydrogen into helium. When all the hydrogen is burnt, helium can itself becomes the fuel. Most stars stop there, puffing off their outer layers into space, so that the enriched gas can become the raw material for the next generation of stars and planets. The remaining core of the star gradually cools becoming a "white dwarf" star, about the size of the Earth.

Not all stars continue shining faintly into a ripe old age. The most massive stars have very short lifetimes that may end in a massive supernova explosion. When such a massive star is blown apart, it may distribute elements such as carbon, oxygen, nitrogen silicon, and sulphur into space. Heavier elements such as nickel can be formed during the supernova explosion itself and scattered into interstellar space. During the explosion, large numbers of gamma-rays are produced and as these pass through the cosmic debris, the newly created elements can be studied by their effect on the gamma-rays. INTEGRAL observations of these gamma-rays will provide the most direct method yet of studying the formation of the elements.

The COMPTEL instrument onboard NASA's Compton Gamma-Ray Observatory has for the first time produced an all-sky map in the light of the 1.8 MeV gamma-ray line produced during the radioactive decay of Al. This diffuse glow – possibly from the remnants of many Galactic supernovae or novae explosions, or the result of stellar winds from very massive young and hot stars – shows the clear presence of the galactic centre and the galactic plane. INTEGRAL will investigate the broad scale distribution of this diffuse radiation with unprecedented sensitivity, energy resolution and imaging. Various "hot spots" in the map could move at various relative velocities – measurable via slight shifts of the energy of the line due to the Doppler effect, and indicating the influence of galactic

3. THE INTEGRAL SPACECRAFT AND INSTRUMENTS

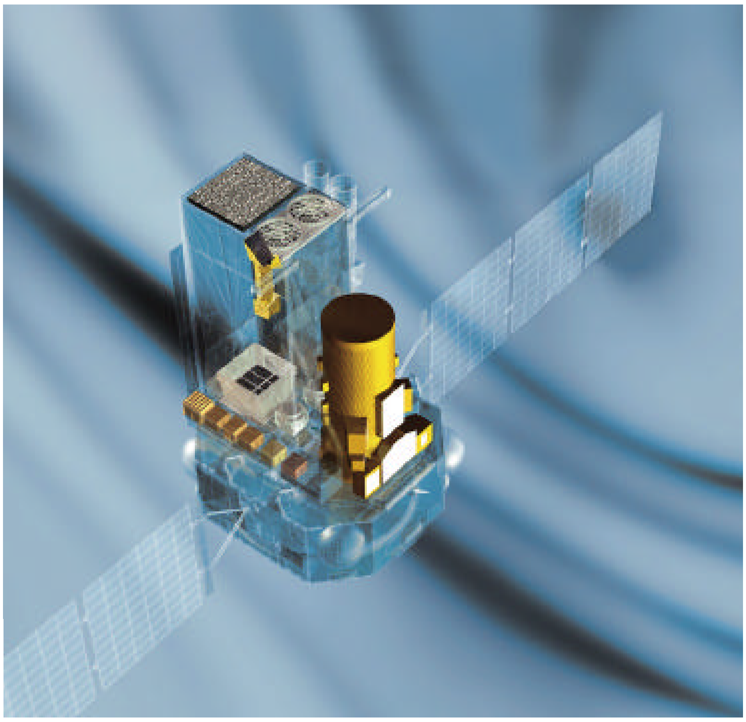

Figure 1. The INTEGRAL instruments. SPI is the cylinder at the front of the spacecraft. IBIS is the large rectangular structure at the rear. The two round JEM-X coded masks are visible in front of IBIS. OMC is mounted on the left of the JEM-X coded masks. Credit: *Medialab*.

The INTEGRAL spacecraft will weigh about 4.1 tonnes at launch and is 5 m tall and 3.7 m in diameter. When the solar panels are deployed they span 16 m. The prime contractor for INTEGRAL is Alenia Areospazio. The spacecraft is composed of two main sections, the service module and the payload module. The service module is the lower part of the satellite. It provides essentials such as power (via solar panels), satellite control and the communications link to the ground. The payload module is connected to the service module and consists of the four scientific instruments. To reduce the cost as much as possible, the service module design was reused from ESA's XMM–Newton satellite.

INTEGRAL will be launched on 17 October 2002 when a Russian Proton rocket will lift the satellite into orbit from Bialonur Cosmodrone in the Republic of Kazakhstan. The Proton will place INTEGRAL into a low parking orbit. About 50 minutes later, another rocket will fire putting INTEGRAL into a transger orbit. The satellite will separate fro the rocket and use its own propulsion system to maneouvre into a final 72-hour orbit with a perigee of 10,000 km, an apogee of 150,000 km and an inclination of 51.6 degrees. This keeps INTEGRAL above the proton radiation belts. These are belts of sub-atomic particles that are trapped by the Earth's magnetic field. Passage through these proton belts would increase the background in the gamma-ray instruments so reducing their sensitivities.

The INTEGRAL payload consists of 4 coaligned instruments that will be operated simultaneously to provide coverage in the optical, X-ray and gamma-ray regions. The properties of the instruments are summarized in Table 1 and their sensitivity to narrow line emission is shown in comparison with some previous gamma-ray missions in Figure 3.

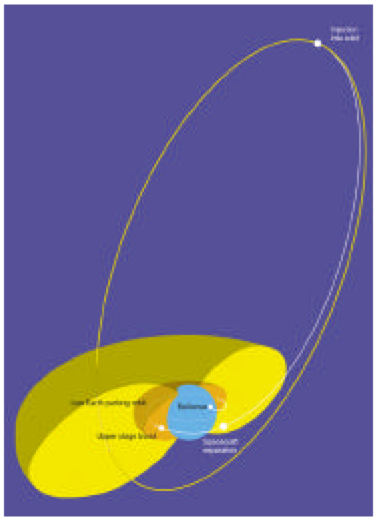

Figure 2. The INTEGRAL orbit

3.1 THE SPECTROMETER (SPI)

The prime goal of SPI (Spectrometer on INTEGRAL) is to perform high-resolution gamma-ray spectroscopy. The instrument will allow the investigation of some of the most energetic phenomena that occur in the Universe such as neutron stars, black holes, supernovae while addressing some of the most fundamental problems in physics and astrophysics such as nuclear de-excitation, positron annihilation and synchrotron emission. SPI has been designed to provide good angular resolution and an excellent energy resolution in the energy range between 20 keV and 8 MeV with imaging and accurate positioning of point sources (<1.0°), or extended gamma-ray emission regions. The detection, shielding and imaging capabilities of high-energy photons by SPI utilises three main features of the instrument: a 19 detector Germanium cooled focal plane, an active shielding telescope and a passive coded tungsten mask. A plastic scintillator located beneath the mask reduces the 511 keV background. The fully coded field of view is 16 degrees in diameter. As a consequence of its construction, SPI is extremely heavy with a mass of 1,300 kg. The principal investigating institutions for SPI are CESR Toulouse, France and MPE Garching, Germany.

3.2 THE IMAGER (IBIS)

The imager IBIS (Imager on Board the INTEGRAL Satellite) is one of the two main instruments onboard INTEGRAL. Simultaneously with the other instruments it will provide high-resolution images of celestial objects of all classes ranging from the most compact galactic systems to extragalactic objects. With better spatial resolution than any previous instrument in the gamma-ray range between 15 keV and 10 MeV, IBIS achieves an angular resolution of 12 arc minutes and an energy resolution of 8 - 9% in the energy range 0.1 - 1 MeV. The source location accuracy is as good as 30 arc seconds for strong sources and the fully coded field of view is 9 by 9 degrees. The imaging capability of the instrument is provided by casting a shadow-gram of a coded mask aperture onto a position sensitive detector. The energy of the incoming gamma-ray photon, transferred to charged particles, is measured using two parallel detector planes surrounded by an active anticoincidence scintillation system. 16384 independent cadmium telluride semiconductor crystals make up the upper layer of the detector and cover the lower gamma-ray energy range between 15 keV and 0.5 MeV. This unit is called ISGRI, for Integral Soft Gamma Ray Imager. Higher energy photons are detected by the lower layer made of 4096 caesium iodide crystal scintillators and called the Pixellated Imager Caesium Iodide Telescope, or PICsIT. In order to reject background events caused by energetic particles, the sides of both detector planes as well as the underside are shielded by an active anti-coincidence system made of Bismute Germanate Oxide (BGO) crystal scintillator blocks read out by photomultiplier tubes. This novel two-layer detector design allows, in principle, the measurement of gamma-ray polarization, as well as allowing the utilisation of the Compton effect to improve the performance, particularly at high energies. The principal investigating institutions for IBIS are IAS Roma, Italy, CEA Saclay, France and TESRE Bologna, Italy.

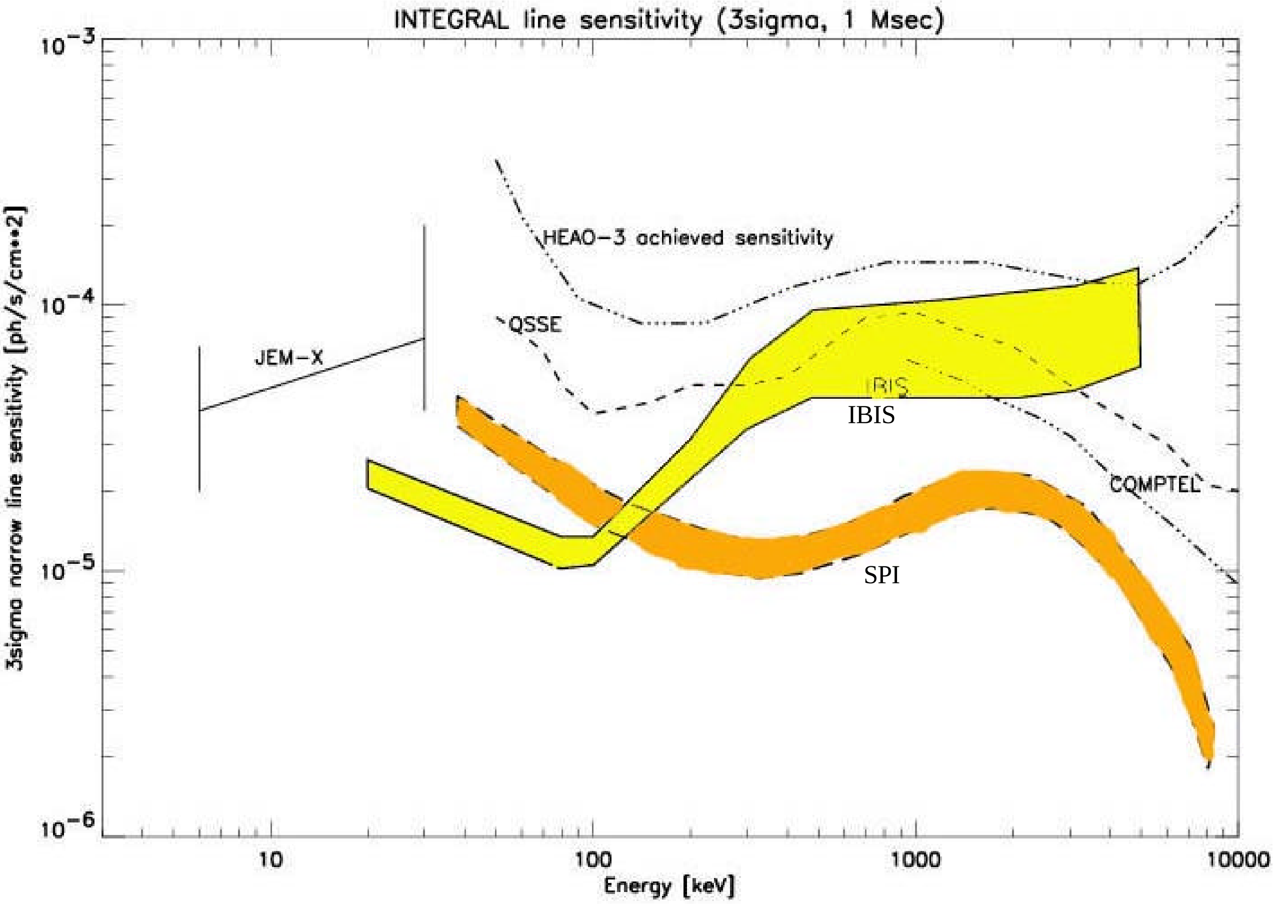

Figure 3. The sensitivity of the INTEGRAL instruments for narrow line emission for a 1 Msec observation. The outstanding sensitivity of SPI above 100 keV is evident, while at energies below this IBIS is even more sensitive. The sensitivity of JEM-X is well matched to these two instruments at lower energies.

3.3 THE X-RAY MONITOR (JEM-X)

The Joint European X-Ray Monitor, JEM-X plays a crucial role in the detection and identification of the gamma-ray sources. JEM-X will make observations simultaneously with the main gamma-ray instruments and will provide images in the 3 to 35 keV energy range with an angular comparable to that of IBIS.

Like IBIS and SPI, it uses the coded mask technique. Two coded masks are located 3.2 m above the detection plane. The detector, a so-called Imaging Micro Strip Gas Counter, consists of two identical gas chambers filled with a mixture of Xenon and Methane at a pressure of 1.4bar, i.e. 1.4times the normal atmospheric pressure at sea level. The principal investigating institution is DSRI, Denmark.

3.4 THE OPTICAL MONITORING CAMERA (OMC)

The OMC offers INTEGRAL the opportunity to make automatically, simultaneous observations of the visible light coming from the gamma ray and X-ray sources. Such observations are particularly important in high-energy astrophysics because emission from a source can change very rapidly. The OMC can register objects of magnitude 18.2 in a 1,000 second exposure and is basically a traditional refracting telescope (i.e. one that uses lens to focus light) with a 5 cm lens and a CCD (charge coupled device) detector in the focal plane. The principal investigating institution is INTA/LAEFF, Spain.

Table 1 – INTEGRAL Instrument Performance Summary

	IBIS	**SPI**	**JEM-X**	**OMC**
Energy Range	15 keV – 10 MeV	15 keV – 8 MeV	3 – 35 keV	V band. Centered on 550 nm
Angular Resolution (FWHM)	12’	2.8 deg	3’	17.6”
Location Accuracy	30” @ 100 keV 60” @ 1 MeV	0.5 deg (90% confidence for a 5σ source).	< 30”	6”
Spectral Resolution (FWHM)	7% at 100 keV 9% at 1 MeV	2.2 keV at 1.33 MeV for each detector	$\Delta E/E = 0.40(E)^{-1/2}$	V-band only
Continuum Sensitivity (3σ in 10^6 s, ph cm^{-2} s^{-1} keV^1)	3.8 10^{-7} @ 100 keV 1-2 10^{-7} at 1 MeV	3 10^{-7} @ 1MeV (ΔE=1MeV)	1.3 10^{-5} @ 6 keV 8.0 10^{-6} @ 30 keV (3σ, 10^6 s)	V = 18.2 for 15 x 100s exposures. (3σ)
Narrow Line sensitivity (ph cm^{-2} s^{-1}, 3σ, 10^6 s)	1.1 10^{-5} @ 100 keV 5 10^{-5} – 10^{-4} @ 1 MeV	2 10^{-5} @ 1 MeV	1.7 10^{-5} @ 6 keV 5.0 10^{-5} @ 30 keV (3σ, 10^6 s)	
Fully Coded FOV	9 x 9 deg	13.2 x 13.2 deg flat to flat (hexagonal)	4.8 deg diameter	5 x 5 deg
Timing	61 µ sec to 30 min	129 µ sec	122 µ sec	> 3 sec

4. THE INTEGRAL SCIENCE GROUND SEGMENT

The INTEGRAL ground segment consists of two major elements, the Operations Ground Segment (OGS) and the Science Ground Segment or SGS. The OGS consists of the Mission Operations Centre (MOC) located at ESOC, the European Space Operations Centre in Darmstadt, Germany and the two tracking stations (Redu in Belgium and Goldstone in California, USA) that INTEGRAL will use.

The SGS itself consists of two components, the INTEGRAL Science Operations Centre (ISOC) which is provided by ESA and the INTEGRAL Science Data Centre (ISDC), which is nationally funded in the same way as the INTEGRAL instruments. The main interfaces and information flows are shown schematically in Fig. 4. The ISOC, located at ESTEC, issues the announcement of opportunities for observing time and handles the incoming proposals. All proposals for observing time on INTEGRAL by the scientific community are assessed by an independent Time Allocation Committee (TAC). The accepted proposals are then processed at the ISOC into an optimised observing plan consisting of a timeline of target positions, together with the corresponding instrument configurations. As part of this optimisation, the ISOC checks for targets close together in the sky which can be observed in a single pointing - so saving observing time. This is particularly important for INTEGRAL where the observations are generally long and the fields of view of the gamma-ray instruments are very large. Optimised observing plans are then forwarded to the Mission Operations Centre at ESOC for the creation of the corresponding commands to be sent to the spacecraft.

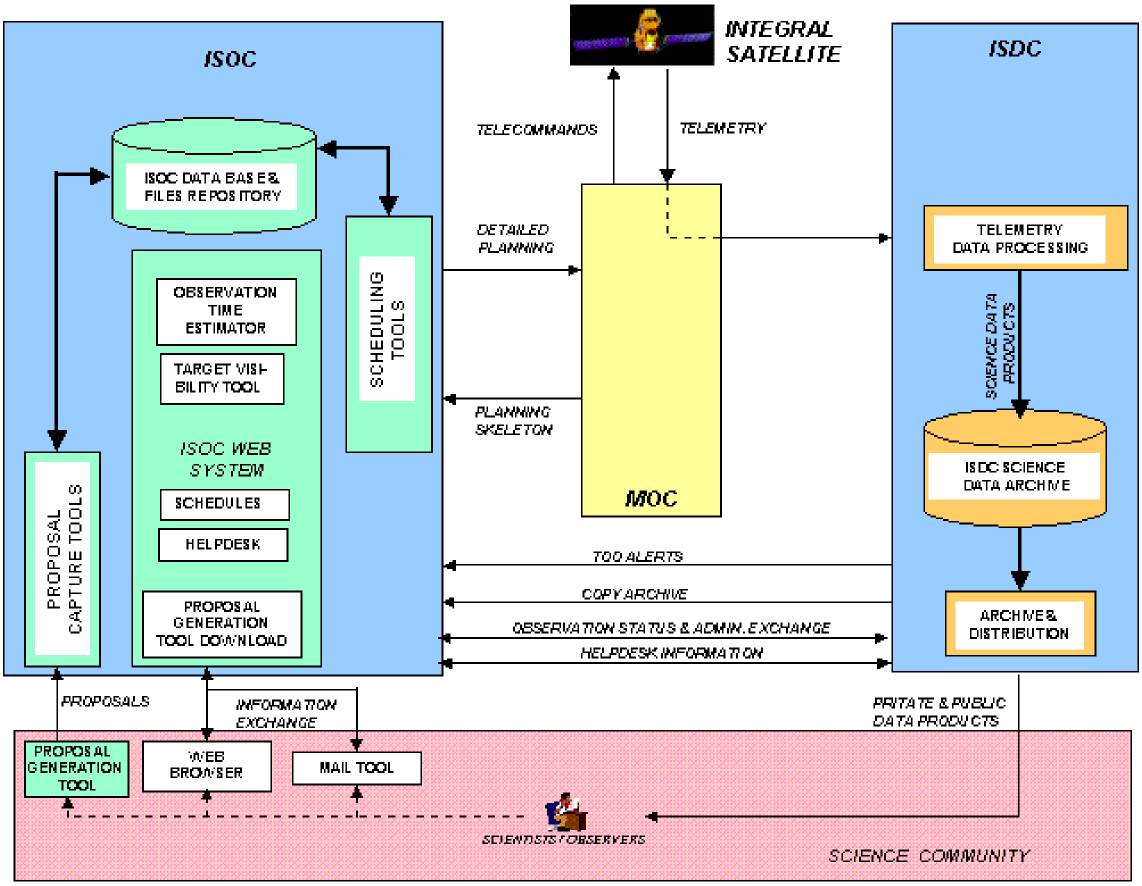

Figure 4. The shaded vertical boxes show the two parts of the INTEGRAL Science Ground Segment (the ISOC and ISDC) together with the main interfaces and information flows with the Mission Operations Centre (MOC), the scientific community and the INTEGRAL satellite.

As discussed above, the gamma-ray sky is very variable and interesting new targets may unexpectedly appear anywhere in the sky. These targets may be discovered using INTEGRAL itself, or by other satellites or ground based observatories. When this happens, the astronomers who made the discovery may request a Target of Opportunity (TOO) observation with INTEGRAL. This is a request to interrupt the already planned sequence of INTEGRAL observations within 20 to 36 hours and observe the newly discovered target due to its high scientific priority. The Project Scientist will decide on the basis of scientific merit whether to proceed with the TOO request. If the request is granted, the ISOC will generate a new observing programme, which will be forwarded to the Missions Operations Centre as before. The revised observing plan will be then made available on the World Wide Web so that astronomers who are planning coordinated observations will know the exact time that INTEGRAL will be observing. In order to support INTEGRAL uses who have questions about any aspect of the mission, or their own observations, there is a Web based helpdesk provided, jointly operated by the ISOC and ISDC.

The ISDC is located in Versoix, Switzerland and will receive raw science telemetry together with relevant ancillary spacecraft data from the OGS. These science data will be processed, taking into account the instrument characteristics, and raw data will be converted into physical units. Using the incoming science and housekeeping information, the ISDC will routinely monitor the instrument science performance and conduct a quick-look science analysis in order to search unusual and interesting events. Many of the TOOs expected during the life of INTEGRAL are likely to be detected at the ISDC in this way. As well as keeping an eye on the long-term health of the instruments, the ISDC will distribute science data products such as images and spectra for all four INTEGRAL instruments. These will be obtained using standard software analysis tools developed by the ISDC and the instrument teams. By using these products astronomers who are not experts on the INTEGRAL instruments will be able to analyse INTEGRAL data. Another very important role for the ISDC is to produce the INTEGRAL science archive for use by the astronomical community. A copy of this archive will be maintained at the ISOC.

5. THE INTEGRAL OBSERVING PROGRAMME

INTEGRAL is an observatory-type mission with a nominal lifetime of 2 years with an extension of up to 5 years technically possible. Most of the observing time (65% during the first year and 70% in year 2) will be awarded competitively to the members of the scientific community. The remaining fraction of time (i.e. 35% in year 1) is reserved for the INTEGRAL Science Working Team (ISWT) for its contribution to the mission. The main task of the ISWT is to monitor and advise ESA on all aspects of the INTEGRAL mission which affect its scientific performance. The ISWT consists of the instrument and ISDC Principal Investigators, representatives of the Russian and the US communities and the Mission Scientists who are independent of the instrument teams. In the first year this "guaranteed time " will be devoted to (1) a galactic plane survey, (2) a deep exposure of the central radian of the Galaxy and (3) pointed observations of selected regions and sources and TOO follow-up observations. In accordance with ESA's policy on data rights, all scientific data will be made available to the scientific community one year after they have been released to the observer. Due to the intrinsically faint source intensities and comparably high background radiation, typical observations will last between about a day to three weeks and observers will receive data from all the simultaneously operating instruments onboard INTEGRAL.

Observing time on a satellite is a very precious resource and INTEGRAL will only be able to carry out the very best of the 291 proposals received when ESA asked for ideas for the first year's observing programme. Indeed, astronomers asked for more than 19 times the open observing time available to INTEGRAL for the first year of operations. This remarkable over-subscription is testament to the scientific capabilities of the mission and the interest of the astronomical community in the topics that INTEGRAL addresses. The open time programme provides for a wide variety of innovative studies of objects and phenomena never before accessible with such a powerful mission. Of the 1-4 accepted proposals, 40 will be devoted to observations of compact objects such as stellar mass black holes and neutron stars, 38 to the study of extragalactic objects such as AGN, 12 to the study of the formation of the elements and 14 to miscellaneous objects (Fig. 5). The TAC selected about twice as many observations as can be performed by INTEGRAL in the first year. This is to allow the ISOC some flexibility in planning which target is observed when in order to minimise the time spent manoeuvring between targets. This planning has to take into account that some observations must be performed at certain times. This normally occurs when an observer needs simultaneous observations with other (ground or space based) observatories, or because the object being studied may be variable and the proposed investigation can only be conducted at certain times (e.g., an observer may wish to study the eclipses of a binary star). In addition, INTEGRAL cannot point at any part on the sky at any time. This is because the solar arrays, which provide INTEGRAL's power, need to be pointed towards the Sun. The best proposals that are unlucky enough not to be scheduled in the first year, will automatically be carried over to the next year.

6. CONCLUSIONS

The INTGRAL satellite will carry instruments with the best combination of line and spectral sensitivities, and spectral and angular resolutions ever into space. A comparison with previous instruments operating in the energy band of INTEGRAL demonstrates that INTEGRAL is capable of making the next step in gamma-ray astronomy.

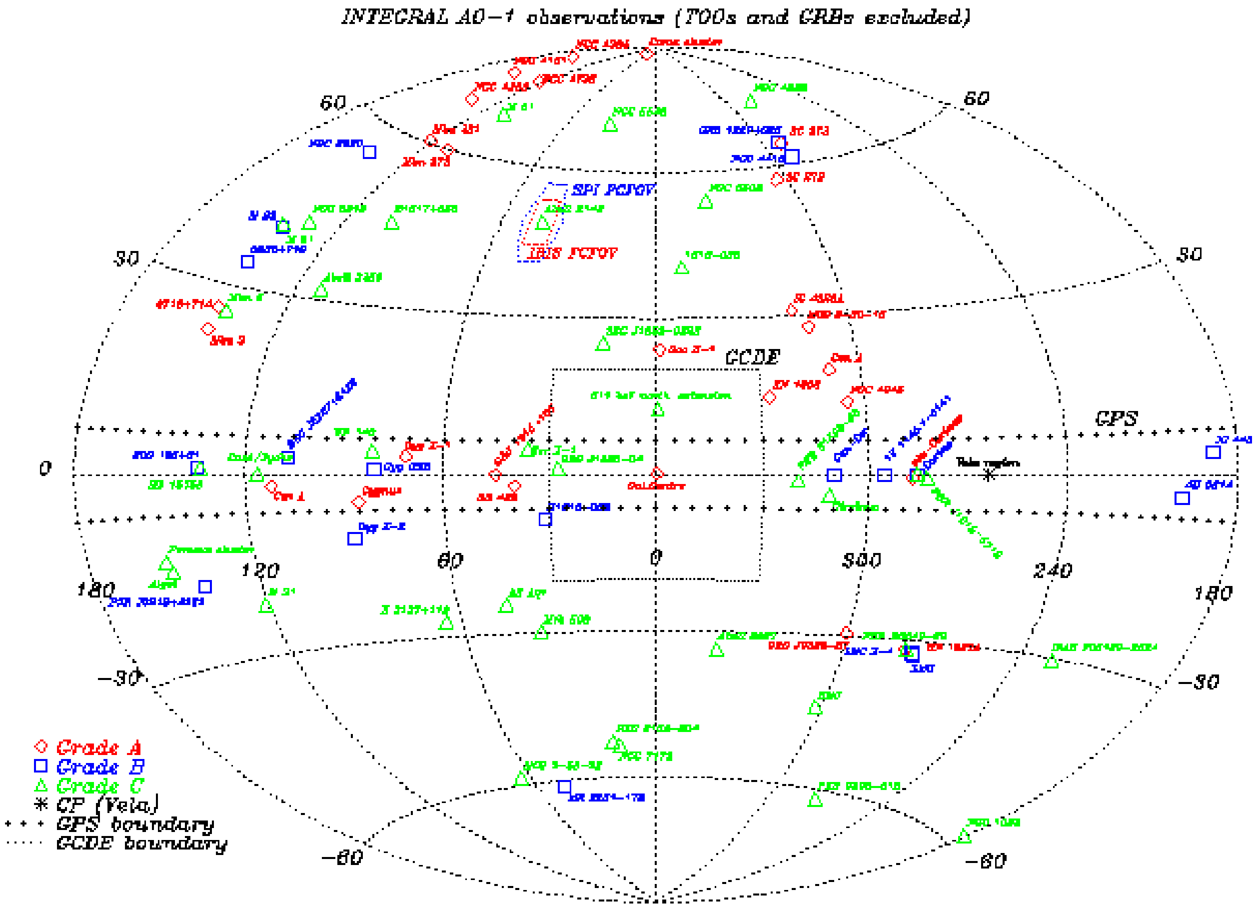

Figure 5. The distribution of INTEGRAL AO-1 targets on the sky in galactic coordinates. The regions covered by the Core Programme galactic plane scans (GPS) and Galactic Centre Deep Exposure (GCDE) are indicated with dotted lines.

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