INTEGRAL

The INTErnational Gamma-Ray Astrophysics Laboratory

Mission Extension 2010: INTEGRAL Science Case

Submitted by the INTEGRAL Users Group

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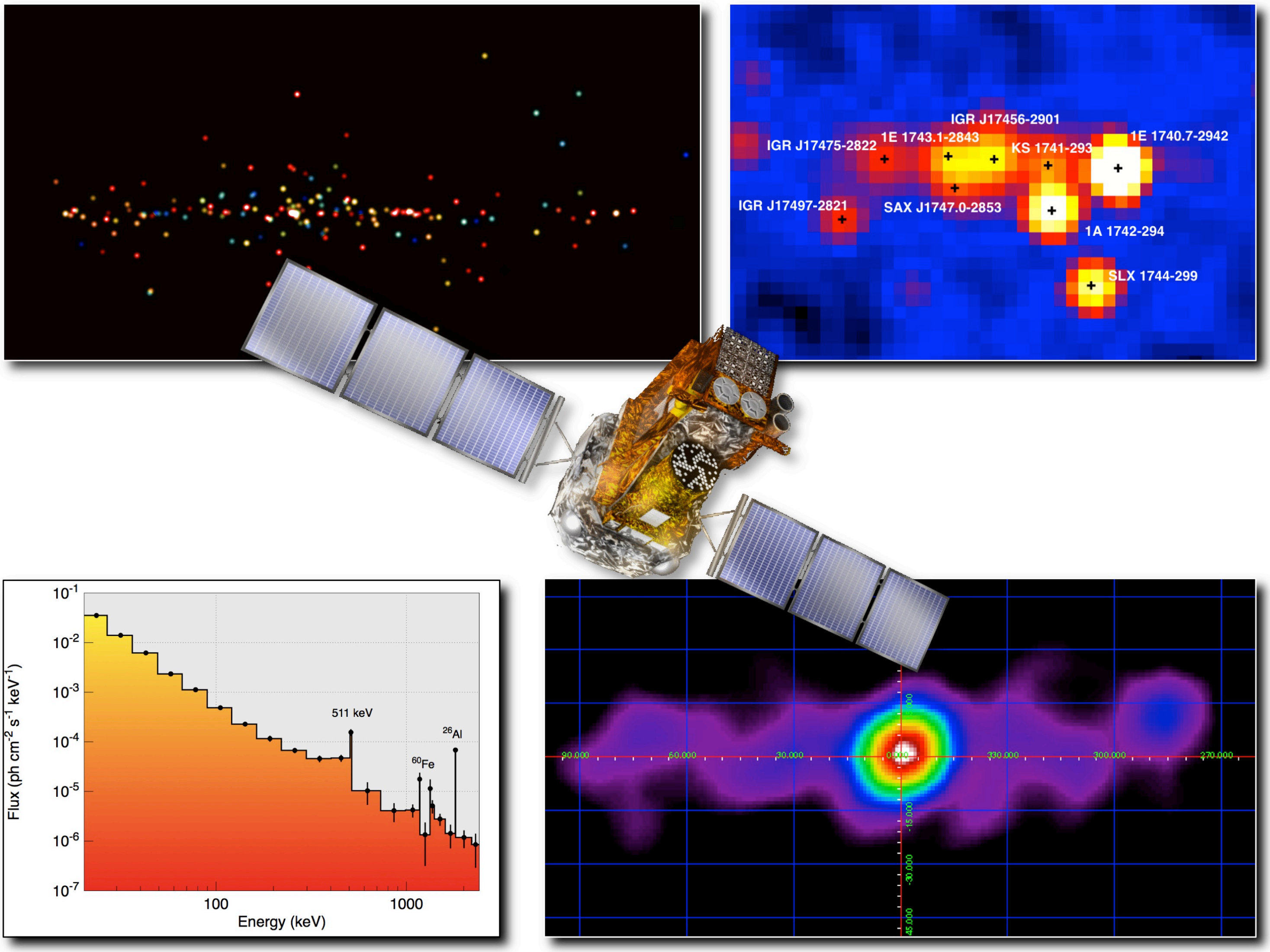

EXECUTIVE SUMMARY

ESA's hard X-ray and soft gamma-ray observatory *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 and keV energy resolution. It links the energy band of pointed soft X-ray missions such as *XMM-Newton* with that of hard gamma-ray facilities such as *Fermi* and ground based TeV observatories. User interest in the observatory is high. No technical issues prevent an extension of the mission until 31 December 2014. For the foreseeable future, *INTEGRAL* will remain the only observatory allowing the study of nucleosynthesis due to massive stars in our Galaxy, including the long overdue next galactic supernova, through high-resolution gamma-ray line observations. Further expected key science results cover a wide span of high-energy astrophysics, including studies of the distribution of positrons in the Galaxy, reflection of gamma-rays off clouds in the interstellar medium near the Galactic Centre, studies of black holes and neutron stars, particularly in high-mass systems, gamma-ray polarisation measurements for X-ray binaries and gamma-ray bursts, and sensitive detection capabilities for obscured active galaxies, with more than 1000 expected to be found until 2014. The *INTEGRAL* Users Group unanimously and strongly recommends the mission extension.

This document and its two appendices (A & B) are available for download at:
http://www.sciops.esa.int/index.php?project=INTEGRAL&page=IUG

INTRODUCTION

ESA's hard X-ray and soft gamma-ray observatory *INTEGRAL* provides the scientific community with a unique energy coverage (3 keV – 10 MeV) and excellent sensitivity in the hard X-ray and soft gamma-ray band (Fig. 1). *INTEGRAL* therefore connects X-ray missions like *XMM-Newton*, *Chandra*, *Suzaku*, *Swift*, and *NuSTAR* (as planned from the end of 2012) with high-energy gamma-ray facilities such as *Fermi*, *AGILE*, and ground based gamma-ray telescopes.

INTEGRAL will remain the only observatory world wide providing these capabilities to the community in this decade.

The observing programme, established through annual Announcements of Opportunity, is characterised by deep (>1 Ms) and often multi-year Key Programme observations, and, in contrast, also by flexible Target of Opportunity observations, enabling *INTEGRAL* to react to transient events of astrophysical significance on the strongly variable gamma-ray sky. The over-subscription in observing time for AO-8 observations (starting in 2011) remains at a high value (3.8) and is comparable to the over-subscription of ~Ms-long Key Programmes of other high-energy astrophysics missions. To make the best possible scientific use of the entire large field of view, the community can also propose for data rights on individual point sources or extended sky regions, which are located in the field of view of the observing programmes, but not included in their original science goals. These sources are simultaneously covered during the observations of the main target. This approach allows the most efficient and timely exploitation of the entire field of view data by various scientific teams. On average, 10 distinct groups of users work on exploiting the science of each observation. Until June 2010, *INTEGRAL* observations have resulted in 545 refereed papers and a total of 1318 publications. We identified at least 74 PhD theses related to *INTEGRAL* science, which have been completed since launch, and another 23 PhD theses are on-going (appendix B). During 2009, on average, 2.2 TByte of scientific data was downloaded per month from the *INTEGRAL* archives at the *INTEGRAL* Science Data Centre, at NASA/HEASARC, and at IKI/RSDC. More than 290 unique visitors per month were counted, and about 1200 visits to archive services (including ftp, ssh, browse) were registered each month.

Key science areas of *INTEGRAL* are:

- **Studies of nucleosynthesis through gamma-ray lines from elements formed in supernovae,**
- **Studies of the physics of emission mechanisms of white dwarfs, neutron stars, and black holes,**
- **Deep surveys for supermassive black holes in Active Galactic Nuclei, and**
- **Observations of gamma-ray bursts.**

INTEGRAL is a pathfinder for future missions, providing extremely good synergy with current and future missions. Numerous new astronomical detectors dedicated to the violent Universe are going to be operational during the extension period, which will start the epoch of multi-messenger astronomy. Among others, these include large radio telescopes (*LOFAR*, *ALMA*, *SKA*), large Cherenkov telescope arrays (*CTA)*, new ultra high-energy cosmic-ray detectors (*AUGER*), large neutrino detectors (*IceCube*, *KM3Net*), and advanced gravitational radiation detectors (*Advanced LIGO*, *Virgo*). In allowing simultaneous observations of various violent phenomena seen in other bands of the electro-magnetic spectrum or even with gravitational radiation or neutrinos, *INTEGRAL* will open new windows on the Universe.

In the following, we give a summary of *INTEGRAL*'s past achievements and expected future science in the above areas. We will demonstrate that *INTEGRAL* is extremely well suited for studying the physics of the high-energy universe and we will show that an extension of *INTEGRAL* observations will result in an excellent opportunity providing answers for a wide variety of important science questions.

NUCLEOSYNTHESIS, SUPERNOVAE, AND GALACTIC STRUCTURE

A key asset of *INTEGRAL* is its high resolution gamma-ray line spectroscopy, which will remain a unique capability for more than a decade to come.

Key results of *INTEGRAL* in this area include:

(1) Electron-positron annihilation emission: The first large-scale sky map at 511 keV gamma-rays was produced by *INTEGRAL* [1]. The origin of the positrons producing this line is a 40-year old mystery. The physical channels capable of producing positrons range from conventional nucleosynthesis up to the decay of dark matter particles. The morphology of the galactic distribution of the 511 keV emission as measured by *INTEGRAL* (Fig. 2) is already constraining the number of possible models.

(2) Diagnostics of past supernovae and supernova remnants: Gamma-ray lines give information on elements freshly created by nucleosynthesis processes. *INTEGRAL* has observed gamma-ray line emission from the long-lived (~1 My) isotopes ^{26}Al and ^{60}Fe, as well as from short-lived ^{44}Ti. Gamma-rays from ^{26}Al in different regions of the sky (Fig. 3) are Doppler-shifted due to large-scale galactic rotation, directly proving its Galaxy-wide origin (Fig. 4), and allowing - using the measured total mass of ^{26}Al - an independent determination of the galactic supernova rate [2]. Line emission from ^{60}Fe was measured at sufficient significance (~5σ) to determine an ^{26}Al/^{60}Fe yield ratio which provides important constraints for models of supernovae originating from massive stars [3]. ^{44}Ti lines at 67.9 keV and 78.4 keV were detected from the young supernova remnant Cas A, clearly showing that this remnant originated from a (very) massive star.

In the early part of the mission, SPI's contribution was primarily the *detection* of gamma-ray lines (see Fig. 5). **In the future, cumulative exposure will allow detailed studies of spectral line shapes and strengths and further studies of the spatial distributions to provide quantitative inputs for astrophysical models for element production.**

The following key results are expected in the next 4 years, taking advantage of dedicated ultra-deep observations, complemented by lower cosmic-ray induced instrumental background.

INTEGRAL will be able to measure possible offsets [4], [5], relative to the Galactic Centre as well as spatial structures in the galactic distribution of the 511 keV emission (Fig. 2). Precision measurements of the line shape and positronium fraction will identify the gas properties of the annihilation site [71]. This will be key information for the determination of the origin of the positrons [72].

INTEGRAL will be able to disentangle ^{26}Al source regions along the line of sight, and thus measure ^{26}Al yields from massive stars in associations (e.g. the Cygnus region [6]).

INTEGRAL will be able to test if the spatial distribution of the ^{60}Fe line emission is consistent with that of ^{26}Al emission and will constrain the dynamics of the hot interstellar medium in the inner Galaxy (as demonstrated through a longitude-velocity diagram for ^{26}Al, [7], see Fig. 4).

INTEGRAL will be able to study in greater detail the inner regions of core-collapse supernovae through the ^{44}Ti gamma-ray line emission (e.g. Cas A). In addition, the homogeneous exposure of the galactic plane is likely to reveal other ^{44}Ti candidates. These results will guide future *NuSTAR* observations of ^{44}Ti, and constrain core-collapse supernova yield models. Similarly, tighter limits on ^{22}Na and ^{7}Be line gamma-rays will establish *INTEGRAL*'s legacy on nova nucleosynthesis.

INTEGRAL will also provide a unique diagnostic to probe the black holes in X-ray transient outbursts through the red-shifted 511 keV line emission.

***INTEGRAL* will be the premier mission to study nucleosynthesis in an exploding star in case of a nearby supernova event, either type Ia at a few Mpc, or a core collapse supernova, like SN 1987A in the LMC (Fig. 6).** Only gamma-rays **directly** measure the radioactivity which powers SN light. Given that there is a chance of such an event during the extended mission operations phase, the opportunity to observe gamma-rays from ^{56}Ni decay (Fig. 6) provides a unique potential for nuclear-line astronomy. Gamma-ray measurements are able to probe dynamics of radioactive ejecta most directly. With *INTEGRAL*, we might well learn more about supernova physics from one such object than from all previous ones combined.

COMPACT GALACTIC SOURCES

***INTEGRAL* is and will remain the leading mission for observations of neutron stars and galactic black holes above 20 keV.** Because of their variability at all timescales, the long and uninterrupted observations provided by *INTEGRAL* are crucial for characterising the physics of these sources. Since they are concentrated in the galactic plane, towards the Galactic Centre, and in the bulge, the large field of view allows studies of a large number and variety of these objects (Fig. 7). *INTEGRAL* discovered in total more than 60 new hard X-ray binaries, doubled the number of known high-mass X-ray binaries [8], and revealed the persistent non-thermal emission from strongly magnetised neutron stars in magnetars.

Key results on compact galactic sources include:

(1) *INTEGRAL* discovered persistent hard X-ray emission from the Centre of the Galaxy [9], [10] (Fig. 8). This emission is not due to the hot plasma seen at lower energies with *Chandra* or *XMM-Newton*, and neither is it due to the central black hole, Sgr A* [11]. *INTEGRAL*'s discovery of hard X-rays from the giant molecular cloud Sgr B2, which are best interpreted as scattering of radiation emitted by Sgr A* more than 100 years ago [12], shows that this non-thermal emission likely traces the past activity of Sgr A*. The most compelling evidence of such reflection is the *INTEGRAL* discovery of Sgr B2 fading in hard X-rays [13] (see Fig. 9). Along with *XMM-Newton* measurements of the Fe K-line variability from other clouds of this region [14], this discovery allowed both the strength to be constrained and the duration of this past activity to be limited. These results established that the behaviour of Sgr A* resembles that of a low-luminosity active galactic nucleus and it might become brighter again in the future. During the continued monitoring of the current activity of Sgr A*, *INTEGRAL* surveys of the Galactic Centre will also allow **the past activity of the closest super-massive black hole** to be monitored by detecting the Compton echo of its outburst radiation as it propagates through the molecular clouds of the region.

(2) *INTEGRAL* discovered the class of strongly absorbed X-ray binaries [15], [16], [69], due to its unique capability to monitor the galactic center/bulge area for long periods at a sensitivity level unreachable by other wide-field instruments. All members of this class known today were discovered with *INTEGRAL*. They are embedded in dense environments (Fig. 7). Their emission is so heavily absorbed that these sources could not be identified earlier with soft X-ray instruments [17], [18], [19]. More than half of these sources have supergiant companions; some of them are X-ray pulsars [20], [21], [22].

(3) *INTEGRAL* discovered Supergiant Fast X-ray Transients (SFXT), i.e., high-mass X-ray binaries that display short X-ray outbursts typically lasting only hours [23], [24]. The total number of these sources is already comparable to that of persistent supergiant X-ray binaries, with new serendipitous discoveries routinely being made. The precise nature of their short outbursts is still debated, mainly due to small source number statistics. There is agreement, however, that it is connected to the mode of stellar wind accretion [25], [26], [27].

(4) *INTEGRAL* discovered that accreting white dwarfs are responsible for a significant fraction of the originally apparently "diffuse" galactic ridge emission [28] (see also Fig. 5). For other accreting systems, long campaigns on neutron star and black hole X-ray binaries revealed the interplay between the different components of the accretion flow such as the cold disk, hot Comptonising plasma, and their synchrotron radiating jets or outflows [29], [30], [31]. *INTEGRAL* detections included: (i) the hard emission up to 1 MeV from black holes; (ii) the non-thermal components >100 keV from neutron star low-mass X-ray binaries [32], [33], [34]; (iii) the Compton up-scattered radiation at >100 keV in accreting millisecond pulsars in outburst [35], [36].

(5) *INTEGRAL* discovered hard tails extending to 200-300 keV in extremely magnetised neutron stars (magnetars), which show a complex dependence on pulse phase. These observations provided new constraints on the geometry and physics of the strongest magnetic fields ($>10^{14}$ G) in the Universe [37], [38], [39], [40], [41] (Fig. 10). In neutron star systems with weaker magnetic fields ($B \sim 10^{12}$ G), cyclotron lines are the only direct way to determine the magnetic field strength of neutron stars ([42] and references therein). *INTEGRAL* monitoring of cyclotron source outbursts (Fig. 11) led to the discovery that the measured line strength is correlated with source luminosity. This result allowed the change in height of the accretion column over the outburst to be traced [43], [44], [45].

INTEGRAL detected the degree and phase-dependence of polarisation in the Crab nebula and pulsar in the hard X-rays through usage of the Compton mode of IBIS [46] and with SPI [47]. Very deep observations of selected bright X-ray sources such as the Vela Pulsar and Cygnus X-1 will allow, for the first time, **the emission geometry in another neutron star and a black hole binary through polarisation measurements to be constrained.** In the soft X-rays, similar data are expected to become available only after 2014 with the launch of NASA's *GEMS* satellite.

Through ultra-deep (~10 Ms) observations of the galactic bulge and arms (Fig. 12), *INTEGRAL* will continue to resolve the galactic ridge emission, to **separate the point source population from the diffuse emission**, and finally detect the predicted low-luminosity source population. Coverage of the extended plane of the Galaxy with high exposure is essential for this science but has not yet been obtained. Disentangling the source contribution from extended diffuse emission provides important information for understanding the gas and energy content of the Galaxy as a whole and its interstellar medium. Through these continued deep observations *INTEGRAL* will also allow **new and rare phenomena in the Galaxy** to be uncovered, such as outbursts of supergiant fast X-ray transients, magnetars, and accreting millisecond pulsars, which cannot be discovered with other missions such as *Swift* or *Fermi*. Only *INTEGRAL* can effectively detect their outbursts and answer basic questions such as: What is the physics behind short outbursts? What are the outburst duty cycles and are they periodic? Is there persistent emission outside outbursts? Observations of further cyclotron lines with *INTEGRAL* will also allow the **number of neutron star systems with directly measured magnetic fields** to be extended (only ~20 are known to date).

Of special interest are GeV and TeV emitting systems. So far, *Fermi, H.E.S.S., and MAGIC* have observed only four binaries emitting radiation up to GeV/TeV energies. An increase in source population is expected as *H.E.S.S.-II* and *MAGIC-2* become operational, *Fermi's* survey gets deeper, and *CTA* is built. The nature of these systems and the origin of the extreme gamma-ray emission are under debate [48]. For these systems, as well as for supernova remnants, pulsar wind nebulae and their pulsars, simultaneous hard X-ray/soft gamma-ray coverage in the gap between X-rays and GeV/TeV is necessary to **understand the non-thermal emission and related particle acceleration processes in GeV/TeV systems**.

SUPERMASSIVE BLACK HOLES, THE COSMIC X-RAY BACKGROUND, AND COSMOLOGY

***INTEGRAL* plays a key role in our understanding of Active Galactic Nuclei (AGN) covering the energy range from 10 keV up to 300 keV where the non-thermal processes are dominant.**

Broad-band spectral analysis of more than 100 AGN has shown that their high-energy radiation is due to thermal Comptonisation of soft photons by a plasma surrounding the central black hole, which is mildly relativistic and has a low optical depth [49], [50]. The latest *INTEGRAL* catalogue [8] has significantly increased the number of these objects detected above 10 keV to more than 250, spanning a large range in redshift ($0 \leq z \leq 3.7$) and luminosities (10^{42} -10^{48} erg/s) (Fig. 13). Most of them are Seyferts 1 and Seyferts 2 in almost equal percentage, while only a few of the brighter Blazars (BL Lac and flat spectrum radio QSOs) have been detected so far.

INTEGRAL is a key instrument in the study of heavily absorbed AGN: it has extensively probed the Compton thin regime ($N_H \leq 1.5\times10^{24}$ cm^{-2}) and it has discovered new Compton thick sources [51]. ***INTEGRAL* has revealed that the percentage of absorbed sources ($N_H > 10^{22}$ cm^{-2}) is ~60%, while the fraction of Compton thick objects ($N_H > 10^{24}$ cm^{-2}) is closer to 10%** [52], [53], [54], [55], in contrast to results obtained from optically selected samples. *INTEGRAL* has also shown a trend of a decreasing fraction of absorbed AGN with increasing hard X-ray luminosities. **In the next 4 years, ultra-deep (≥10 Ms) observations will permit to disentangle whether this is a direct consequence of the evolution of the AGN luminosity function with redshift.** We anticipate the number of high-energy detected AGN will double as every optical spectroscopic follow-up campaign finds new AGN among the unidentified IBIS sources. Most important, as the sky exposure deepens in the next four years, other types of high-energy AGN will emerge and their physics will be studied in *INTEGRAL's* hard X-ray/soft gamma-ray range for the first time, complemented below ~70 keV with *NuSTAR's* follow up observations.

INTEGRAL will also provide unique and essential observational coverage in the soft gamma-ray domain for different AGN classes in synergy with X-ray and gamma-ray observatories, ground based TeV telescopes, and radio-*VLBI* monitoring of their jets. Long term monitoring of the variability for several very bright AGN is needed to unveil the geometry and the physics of the accretion on the central engine in the non-thermal regime. Wide-band *INTEGRAL* spectra are and will be a unique tool to characterise the primary spectral shape of AGN, which is of paramount importance for synthesis models of the Cosmic X-Ray Background (CXB), as they will provide key parameters such as power law index, cut-off energy and the strength of any reflection component. *INTEGRAL* has provided first direct comparison between the collective hard X-ray SED of local AGN and the CXB spectrum in the 3–300 keV energy range [70].

The main objective for the coming four years will be the observation of a large sample of jet-dominated Blazars, jointly with *Fermi*, ground based gamma-ray facilities, and radio-*VLBI*. **Such studies will provide an independent insight into the**

physics of jets with *INTEGRAL*'s unique sensitivity achieved in deep extragalactic fields. Some of those Blazars have the most powerful jets, larger black hole masses and more luminous accretion disks: their spectral energy distribution has a Compton peak in the MeV to sub-MeV region [56], [57]. The *INTEGRAL* discovery of such massive objects is shedding a new light on the co-evolution of black holes and galaxies and starts to probe the initial supermassive black hole [58]. Reaching an ultra deep exposure in the next few years is of paramount importance in order to discover hard X-ray emitting Blazars that will provide a new perspective into jet dominated sources thereby complementing and superseding the standard optical classification. ***INTEGRAL* observations will allow a unique investigation of the recently suggested contribution of Blazars to the diffuse gamma-ray continuum in the 100-300 keV range, where that of Seyferts is decreasing exponentially.** Additional observations, using the Earth as a "blocking device" (see [67], [68] for initial results), will be performed to determine the integrated hard X-ray background flux with *INTEGRAL*.

Observations with *INTEGRAL* will add fundamental information to our overall knowledge of supermassive black hole activation, unification, and evolution and provide an invaluable database from which to select the main scientific targets for the forthcoming hard X-ray missions, such as *NuSTAR* and *ASTRO-H*. The *INTEGRAL* survey capability, utilizing its unique ~100 □° field of view will be complemented by *NuSTAR's* superior resolving power and sensitivity follow-up provided below 70 keV. In fact, *NuSTAR* (and *ASTRO-H*) would need, due to the small field of view of about 0.05 □°, about 10^6 separate pointings to cover the entire sky.

The high-energy survey legacy of *INTEGRAL* and *Swift/BAT* will therefore remain unique for the next decades and the "decade long" unbiased *INTEGRAL* survey will be of seminal importance for extragalactic astronomers, comprising around 1500 sources by the end of 2014 (Fig. 14).

GAMMA-RAY BURSTS

INTEGRAL is one of the major facilities for studying Gamma-Ray Bursts (GRB) above 20 keV. Real time, arc-minute positions of GRB imaged with IBIS are distributed via the WWW at a rate of about 10 per year (75 to date), the weakest GRB with a fluence of ~5×10^{-8} erg cm^{-2} [59]. Follow-up observations by *Swift*, *XMM-Newton*, and ground-based observatories have revealed 45 X-ray, optical, and/or radio counterparts to these events, with redshifts between z=0.105 and 3.793. The SPI ACS has played a key role in localising and identifying two events, which are believed to be extragalactic giant magnetar flares from M81 and M31 [60], [61]. As *LIGO* was operative at the time of the M31 event, neutron star-neutron star mergers could for the first time definitively be excluded for these events, whereas the data are consistent with the magnetar flare hypothesis [62].

Compared to *Swift*, ***INTEGRAL* with its unique sensitivity detects a larger number of faint GRB (Fig. 15). This is essential to investigate the fraction of GRB with long spectral lags, which appear to be a low-luminosity population distinct from the high-luminosity one and which is inferred to be local [63] - an important *INTEGRAL* discovery. This evidence will be confirmed in the next 4 years almost doubling the sample, also in view of the increasing detector sensitivity.**

INTEGRAL will remain the only mission with the arc-minute imaging capability and wide band sensitivity necessary to measure prompt GRB emission in the range from 15 keV to 10 MeV (Fig. 15). **The detection of polarisation in GRB 041219a with *INTEGRAL* has opened a new observational window** providing information on the physical mechanism by which the central engine of a GRB emits the huge observed energies, a presently unresolved but crucial issue [64], [65], [66]. Observing another bright GRB in the field of view of *INTEGRAL* is crucial to confirm the previous results.

IUG RECOMMENDATION ON THE INTEGRAL MISSION EXTENSION

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 strong potential of discoveries from future observations, the continued interest by the scientific community in the *INTEGRAL* mission, the success of the *INTEGRAL* Key Programmes, and the synergies with existing and future space missions and ground based observatories. The Users Group also stresses that with the successful transition to merged operations between *XMM-Newton* and *INTEGRAL*, cost savings have been maximised while retaining full scientific performance.