PROSPECTS IN SPACE-BASED GAMMA-RAY ASTRONOMY

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Abstract

At the uppermost part of the electromagnetic spectrum, observations of the gamma-ray sky reveal the most powerful sources and the most violent events in the Universe. While at lower wavebands the observed emission is generally dominated by thermal processes, the gamma-ray sky provides us with a view on the non-thermal Universe, where particles are accelerated by still poorly understood mechanisms to extremely relativistic energies, and nuclear interactions, reactions, and decays are organising the basic elements of which our world is made of. Cosmic accelerators and cosmic explosions are the major science themes that are addressed in this waveband.

With the unequalled INTEGRAL observatory, ESA has provided a unique tool to the astronomical community that has made Europe the world leader in the field of gamma-ray astronomy. INTEGRAL provides an unprecedented survey of the soft gamma-ray sky, revealing hundreds of sources of different kinds, new classes of objects, extraordinary views of antimatter annihilation in our Galaxy, and fingerprints of recent nucleosynthesis processes.

While INTEGRAL provides the longly awaited global overview over the soft gamma-ray sky, there is a growing need to perform deeper, more focused investigations of gamma-ray sources, comparable to the step that has been taken in X-rays by going from the ROSAT survey satellite to the more focused XMM-Newton observatory. Technological advances in the past years in the domain of gamma-ray focusing using Laue diffraction techniques have paved the way towards a future European gamma-ray mission, that will outreach past missions by large factors in sensitivity and angular resolution. Such a future *Gamma-Ray Imager* will allow to study particle acceleration processes and explosion physics in unprecedented depth, providing essential clues on the intimate nature of the most violent and most energetic processes in the Universe.

Key words: Gamma-ray astronomy – cosmic accelerators – cosmic explosions

1. Introduction

Since the early days of space-science, the field of gamma-ray astronomy has played an important role in Europe. As early as in 1975, ESA launched the COS-B satellite which provided the first extensive survey of the Galaxy in the energy range 50 MeV to 5 GeV. Since then, European researchers have contributed in various manners to the development of the field, either by the design and exploitation of dedicated instruments, such as the French-Russian SIGMA telescope or the Italian-Dutch BeppoSAX satellite, or by the participation in international collaborations, such as NASA's Compton Gamma-Ray Observatory (CGRO) or the recently launched Swift mission. These developments culminate today with the scientific exploitation of ESA's INTEGRAL observatory, a mission that actually places Europe as the world leader in the field. With its unprecedented combination of good sensitivity and excellent imaging and spectroscopic capabilities, INTEGRAL provides a new and unique view of the soft gamma-ray sky, and will provide the setting of the field for the next decade.

In the process of defining ESA's space science program for the decade 2015–2025, it is legitimate to ask the question why our sky should be explored in gamma-rays, why gamma-ray astronomy should be performed in Europe, and what kind of instrument should follow the on-going INTEGRAL mission. The aim of this paper is to suggest answers to these questions. These answers have been collected from the European gamma-ray community during a prospects seminar that was held on March 18th, 2005 in Rome (see the web-site `http://www.cesr.fr/~jurgen/rome2005/`).

2. Why gamma-ray astronomy?

As introductory remark, it is worth emphasising some unique features of gamma-ray astronomy: the specific character of the emission processes, the diversity of the emission sites, and the penetrating nature of the emission.

First, the emission process that leads to gamma-rays is in general very specific, and as such, is rarely observable in other wavebands. At gamma-ray energies, cosmic acceleration processes are dominant, while in the other wavebands thermal processes are generally at the origin of the emission. For example, electrons accelerated to relativistic energies radiate gamma-ray photons of all energies through electromagnetic interactions with nuclei, photons, or intense magnetic fields. Accelerated protons generate secondary particles through nuclear interactions, which may decay by emission of high-energy gamma-ray photons. At gamma-ray energies, nuclear deexcitations lead to a manifold of line features, while in the other wavebands, it is the bound electrons that lead to atomic or molecular transition lines. For example, the radioactive decay of tracer isotopes allows the study of nucleosynthesis processes that occur in the deep inner layers of stars. The interaction of high-energy nuclei with the gas of the interstellar medium produces a wealth of excitation lines that probe the composition and energy spectrum of the interacting particles. Finally, annihilation between electrons and positrons result in a unique signature at 511 keV that allows the study of antimatter in the Universe.

Second, the sites of gamma-ray emission in the Universe are very diverse, and reach from the nearby Sun up to the distant Gamma-Ray Bursts and the cosmic gamma-ray background radiation. Cosmic acceleration takes place on all scales: locally in solar flares, within our Galaxy (e.g. in compact binaries, pulsars, supernova remnants), and also in distant objects (such as active galactic nuclei or gamma-ray bursts). Cosmic explosions are another site of prominent gamma-ray emission. They produce a wealth of radioactive isotopes, are potential sources of antimatter, and accelerate particles to relativistic energies. Novae, supernovae and hypernovae are thus prime targets of gamma-ray astronomy.

Third, gamma-rays are highly penetrating, allowing the study of otherwise obscured regions. Examples are regions of the galactic disk hidden by dense interstellar clouds, or the deeper, inner, zones of some celestial bodies, where the most fundamental emission processes are at work. New classes of sources become visible in the gamma-ray domain, that are invisible otherwise.

In summary, gamma-ray astronomy provides a unique view of our Universe. It unveils specific emission processes, a large diversity of emission sites, and probes deeply into the otherwise obscured high-energy engines of our Universe. The gamma-ray Universe is the Universe of particle acceleration and nuclear physics, of cosmic explosions and non-thermal phenomena. Exploring the gamma-ray sky means exploring this unique face of our world, the face of the evolving violent Universe.

3. Cosmic accelerators

3.1. The link between accretion and ejection

As a general rule, accretion in astrophysical systems is often accompanied by mass outflows, which in the high-energy domain take the form of (highly) relativistic jets. Accreting objects are therefore powerful particle accelerators, that can manifest on the galactic scale as micro-

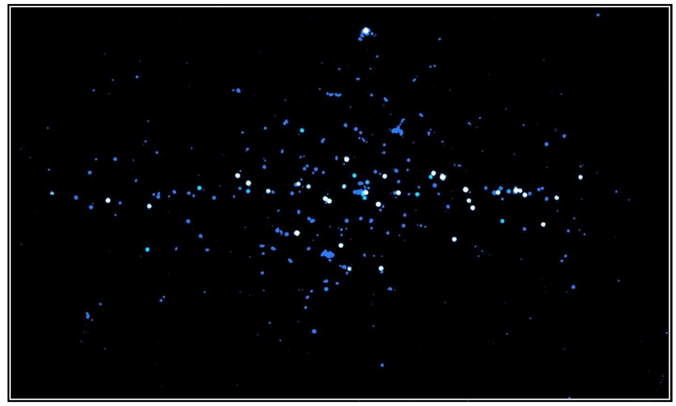

Figure 1. The hard X-ray sky resolved into individual point sources by the IBIS telescope aboard INTEGRAL (Lebrun et al. 2004).

quasars, or on the cosmological scale, as active galactic nuclei, such as Seyfert galaxies and Blazars.

Although the phenomenon is relatively widespread, the jet formation process is still poorly understood. It is still unclear how the energy reservoir of an accreting system is transformed in an outflow of relativistic particles. Jets are not always persistent but often transient phenomena, and it is still not known what triggers the sporadic outbursts in accreting systems. Also, the collimation of the jets is poorly understood, and in general, the composition of the accelerated particle plasma is not known (electron-ion plasma, electron-positron pair plasma). Finally, the radiation processes that occur in jets are not well established.

Observations in the gamma-ray domain are able to provide a number of clues to these questions. Gamma-rays probe the innermost regions of the accreting systems that are not accessible in other wavebands, providing the closest view to the accelerating engine. Time variability and polarisation studies provide important insights into the physical processes and the geometry that govern the acceleration site. The accelerated plasma may reveal its nature through characteristic nuclear and/or annihilation line features which may help to settle the question about the nature of the accelerated plasma.

3.2. The origin of galactic soft γ-ray emission

Since decades, the nature of the galactic hard X-ray (> 15 keV) emission has been one of the most challenging mysteries in the field. The INTEGRAL imager IBIS has now finally solved this puzzle. At least 90% of the emission has been resolved into point sources, settling the debate about the origin of the emission (c.f. Fig. 1; Lebrun et al. 2004).

At higher energies, say above ~ 300 keV where the soft gamma-ray band starts, the situation is less clear. In this domain, only a small part of the galactic emission has so far been resolved into point sources, and the nature of the bulk of the galactic emission is so far unexplained. That a new kind of object or emission mechanism should be at work in this domain is already suggested by the change of the slope of the galactic emission spectrum. While below ~ 300 keV the spectrum can be explained by a superposition of Comptonisation spectra from individual point sources, the spectrum turns into a powerlaw above this energy, which is reminiscent of particle acceleration processes. Identifying the source of this particle acceleration process, i.e. identifying the origin of the galactic soft gamma-ray emission, is one of the major goals of a future European gamma-ray mission.

One of the strategies to resolve this puzzle is to follow the successful road shown by INTEGRAL for the hard X-ray emission: trying to resolve the emission into individual point sources. Indeed, a number of galactic sources show powerlaw spectra in the gamma-ray band, such as supernova remnants, like the Crab nebula, or some of the black-hole binary systems, like Cyg X-1 (Mc Connell et al. 2000). Searching for the hard powerlaw emission tails in these objects is therefore a key objective for a future gamma-ray mission.

3.3. The origin of the soft γ-ray background

After the achievements of XMM-Newton and Chandra, the origin of the cosmic X-ray background (CXB) is now basically solved for energies close to a few keV. However, whilst the CXB is $\sim 85\%$ and 80% resolved in the 0.5–2 keV and 2–10 keV bands, respectively, it is only $\sim 50\%$ resolved above ~ 8 keV (Worsley et al. 2005). The situation is even worse in the soft gamma-ray band. Although about 20% of the sources detected in the second IBIS catalogue are of extragalactic nature (Bassani et al. 2005) they only account for 1% of the background emission seen in the 20-100 keV band, i.e. where the bulk of the soft γ-ray background energy density is found.

Looking from another point of view, synthesis models, which are well established and tested against observational results, can be used to evaluate the integrated AGN contribution to the soft γ-ray background. Unfortunately, they lack some key information at high energies: the absorption distribution is currently biased against low column densities due to the lack of soft gamma-ray surveys, no AGN luminosity function is available above 10 keV nor has the input spectral shape of the different classes of AGN been firmly established at high energies. Furthermore, the integrated AGN contribution changes as a function of model input parameters. As an illustration, Fig. 2 shows how different results can be obtained by varying the power law energy cut-off. A large region of this parameter space is virtually unexplored because we currently lack information on large AGN samples. Observations by BeppoSAX (Risaliti 2002; Perola et al. 2002) of a handful of radio quiet sources, loosely locate this drop-off in the range 30–300 keV; furthermore these measurements give evidence for a variable cut-off energy and suggest that it may increase with increasing photon index (Perola et al. 2002). In radio loud sources the situation is even more complicated with some objects showing a power law break and others no cut-off up to the MeV region. In a couple of low luminosity AGN no cut-off is present up to 300–500 keV. The overall picture suggests some link with the absence (low energy cut-off) or presence (high energy cut-off) of jets in the various AGN types sampled, but the data are still too scarce for a good understanding of the processes involved. One method to tackle this issue is to measure the soft gamma-ray SED (power law continuum plus high energy cut-off as well as hard tails if present) in a sizeable fraction of AGN in order to determine average shapes in individual classes and so the nature of the radiation processes at the heart of all AGN. This would provide at the same time information for soft γ-ray background synthesis models. On the other hand, sensitive deep field observations should be able to resolve the soft γ-ray background into individual sources, allowing for the ultimate identification of the origin of the emission.

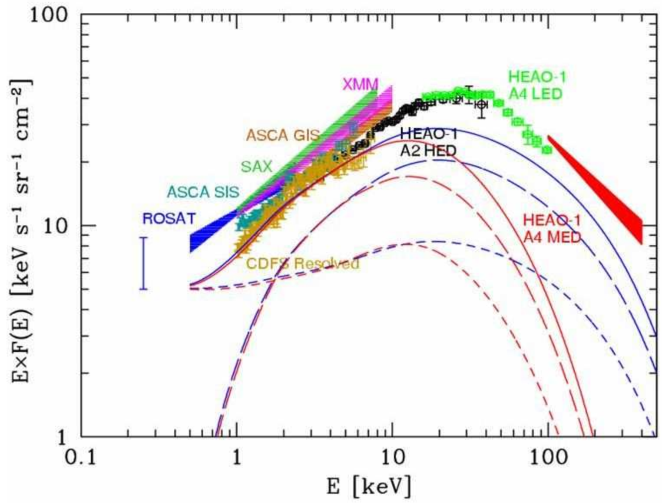

Figure 2. The 0.25–400 keV cosmic X-/γ−ray background spectrum fitted with synthesis models; measurements are from observations with different experiments as labelled. Solid curves represent the integrated contribution of synthesis models: blue corresponds to an AGN spectrum with cut-off at 400 keV while and red to one with cut-off at 100 keV. The short–dashed curves correspond to unabsorbed AGN ($\log N_H < 22$ cm^{-2}), while the long–dashed curves correspond to obscured Compton thin sources ($\log N_H$ in the range 22–24 cm^{-2}). Figure from Comastri (2004).

3.4. Particle acceleration in extreme B-fields

The strong magnetic fields that occur at the surface of neutron stars in combination with their fast rotation make them to powerful electrodynamic particle accelerators,

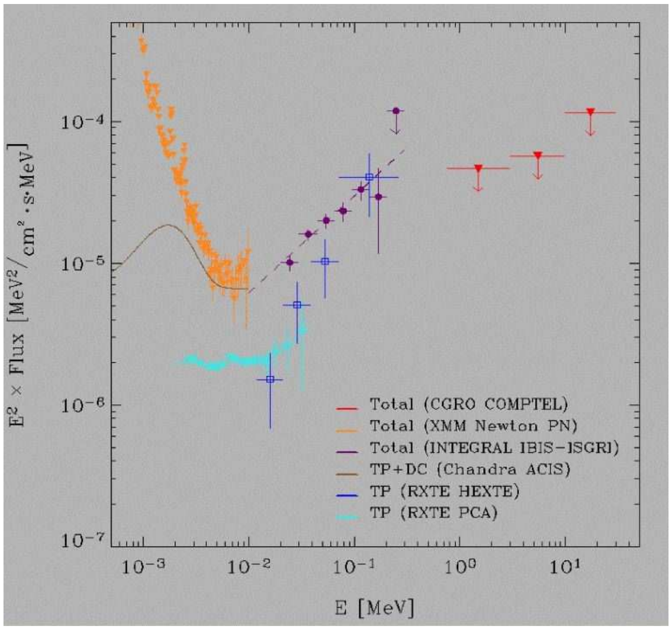

Figure 3. High-energy spectral energy distribution of AXP 1E 1841-045 (Kuiper et al. 2004).

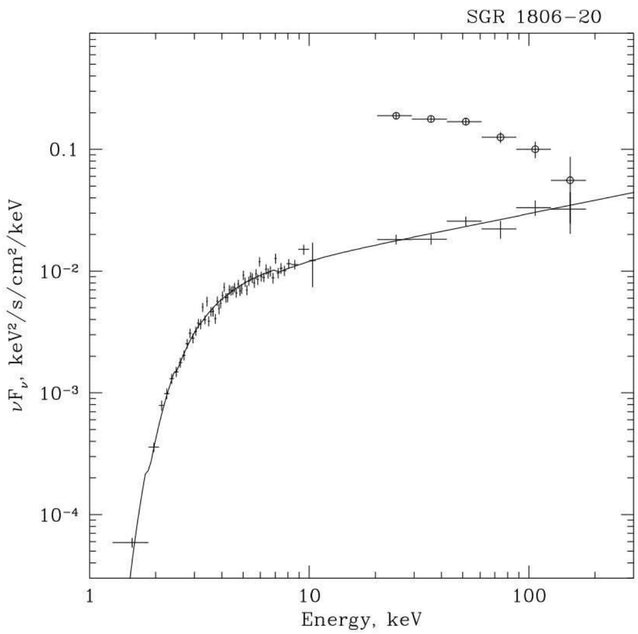

Figure 4. The quiescent energy spectrum of SGR 1806-20 (lower spectrum) and the summed spectrum of all detected bursts rescaled down by a factor of 1000 (upper spectrum). From Molkov et al. (2005).

which may manifest as pulsars to the observer. Gamma-ray emitting pulsars can be divided into 3 classes: spin-down powered pulsars, such as normal or millisecond pulsars, accretion powered pulsars, occurring in low-mass or high-mass binary systems, and magnetically powered pulsars, known as magentars.

Despite the longstanding efforts in understanding the physics of spin-down powered pulsars, the site of the gamma-ray production within the magnetosphere (outer gap or polar cap) and the physical process at action (synchrotron emission, curvature radiation, inverse Compton scattering) remain undetermined. Although most of the pulsars are expected to reach their maximum luminosity in the MeV domain, the relatively weak photon fluxes have only allowed the study of a handful of objects so far. Increasing the statistics will allow the study of the pulsar lightcurves over a much broader energy range than today, providing crucial clues on the acceleration physics of these objects.

Before the launch of INTEGRAL, the class of anomalous X-ray pulsars (AXPs), suggested to form a sub-class of the magnetar population, were believed to exhibit very soft X-ray spectra. This picture, however, changed dramatically with the detection of AXPs in the soft gamma-ray band by INTEGRAL (Kuiper et al. 2004). In fact, above ~ 10 keV a dramatic upturn is observed in the spectra which is expected to cumulate in the 100 keV – 1 MeV domain (c.f. Fig. 3). The same is true for Soft Gamma-ray Repeaters (SGRs), as illustrated by the recent discovery of quiescent soft gamma-ray emission from SGR 1806-20 by INTEGRAL (c.f. Fig. 4; Molkov et al. 2005). The process that gives rise to the observed gamma-ray emission in still unknown. No high-energy cut-off has so far been observed in the spectra, yet upper limits in the MeV domain indicate that such a cut-off should be present. Determining this cut-off may provide important insights in the physical nature of the emission process, and in particular, about the role of QED effects, such as photon splitting, in the extreme magnetic field that occur in such objects. Strong polarisation is expected for the high-energy emission from these exotic objects, and polarisation measurements may reveal crucial to disentangle the nature of the emission process and the geometry of the emitting region. Complementary measurements of cyclotron features in the spectra provide the most direct measure of the magnetic field strengths, complementing our knowledge of the physical parameters of the systems.

4. Cosmic explosions

4.1. Understanding Type Ia supernovae

Although hundreds of Type Ia supernovae are observed each year, and although their optical lightcurves and spectra are studied in great detail, the intimate nature of these events is still unknown. Following common wisdom, Type Ia supernovae are believed to arise in binary systems where matter is accreted from a normal star onto a white dwarf. Once the white dwarf exceeds the Chandrasekhar mass limit a thermonuclear runaway occurs that leads to its incineration and disruption. However, attempts to model the accretion process have so far failed to allow for

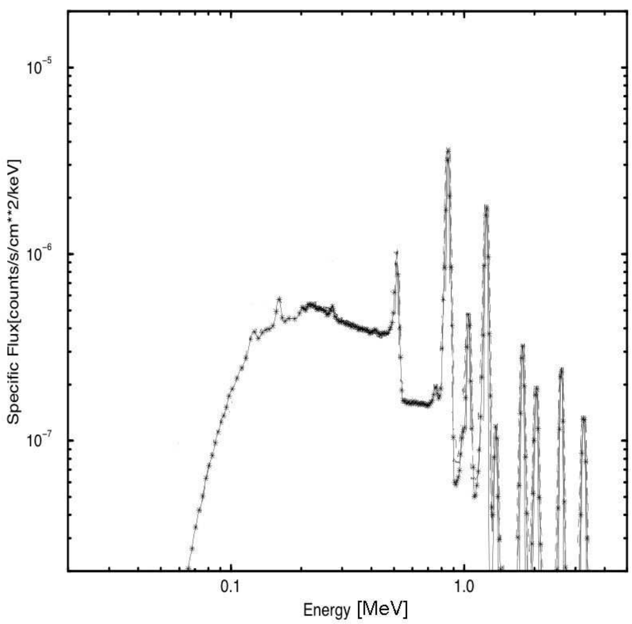

Figure 5. Simulated gamma-ray spectrum of a Type Ia supernova (Gomez-Gomar et al. 1998).

sufficient mass accretion that would push the white dwarf over its stability limit (Hillebrandt & Niemeyer 2000). Even worse, there is no firm clue that Type Ia progenitors are indeed binary systems composed of a white dwarf and a normal star. Alternatively, the merging of two white dwarfs in a close binary system could also explain the observable features of Type Ia events (e.g. Livio & Riess 2003). Finally, the explosion mechanism of the white dwarf is only poorly understood, principally due to the impossibility to reliably model the nuclear flame propagation in such objects (Hillebrandt & Niemeyer 2000).

In view of all these uncertainties it seems more than surprising that Type Ia are widely considered as standard candles. In particular, it is this standard candle hypothesis that is the basis of one of the fundamental discoveries of the last decade: that the expansion of the Universe is currently accelerating (Riess et al. 1998). Although empirical corrections to the observed optical lightcurves seem to allow for some kind of standardisation, there is increasing evidence that Type Ia supernovae are not an homogeneous class of objects (e.g. Mannucci et al. 2005).

Gamma-ray observation of Type Ia supernovae provide a new and unique view of these events. Nucleosynthetic products of the thermonuclear runaway lead to a rich spectrum of gamma-ray line and continuum emission that contains a wealth of information on the progenitor system, the explosion mechanism, the system configuration, and its evolution (c.f. Fig. 5). In particular, the radioactive decays of ^{56}Ni and ^{56}Co, which power the optical lightcurve which is so crucial for the cosmological interpretation of distant Type Ia events, can be directly observed in the gamma-ray domain, allowing to pinpoint the underlying progenitor and explosion scenario. The comparison of the gamma-ray to the optical lightcurve will provide direct information about energy recycling in the supernova envelope that will allow a physical (and not only empirical) calibration of Type Ia events as standard candles.

In addition to line intensities and lightcurves, the shapes of the gamma-ray lines hold important informations about the explosion dynamics and the matter stratification in the system. Measuring the line shapes (and their time evolution) will allow to distinguish between the different explosion scenarios, ultimately revealing the mechanism that creates these most violent events in the Universe (Gomez-Gomar et al. 1998).

4.2. Nova nucleosynthesis

Classical novae are another site of explosive nucleosynthesis that is still only partially understood (see Hernanz et al., these proceedings). Although observed elemental abundances in novae ejecta are relatively well matched by theoretical models, the observed amount of matter that is ejected substantially exceeds expectations. How well do we really understand the physics of classical novae?

Radioactive isotopes that are produced during the nova explosion can serve as tracer elements to study these events. Gamma-ray lines are expected from relatively long living isotopes, such as ^{7}Be and ^{22}Na, and from positron annihilation of β^{+}-decay positrons arising from the short living ^{13}N and ^{18}F isotopes. Observation of the gamma-ray lines that arise from these isotopes may improve our insight into the physical processes that govern the explosion. In particular, they provide information on the composition of the white dwarf outer layers, the mixing of the envelop during the explosion, and the nucleosynthetic yields. Observing a sizeable sample of galactic nova events in gamma-rays should considerably improve our understanding of the processes at work, and help to better understand the underlying physics.

4.3. Understanding core-collapse explosions

Gamma-ray line and continuum observations address some of the most fundamental questions of core-collapse supernovae: how and where the large neutrino fluxes couple to the stellar ejecta; how asymmetric the explosions are, including whether jets form; and what are quantitative nucleosynthesis yields from both static and explosive burning processes?

The ejected mass of ^{44}Ti, which is produced in the innermost ejecta and fallback matter that experiences the alpha-rich freezeout of nuclear statistical equilibrium, can be measured to a precision of several percent in SN 1987A. Along with other isotopic yields already known, this will provide an unprecedented constraint on models of that event. ^{44}Ti can also be measured and mapped, in angle

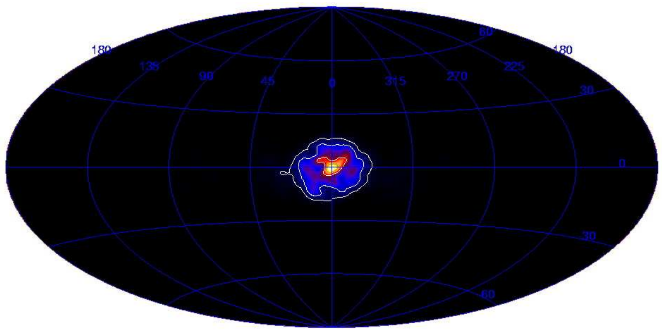

Figure 6. First all-sky map of 511 keV electron-positron annihilation radiation as observed by the SPI telescope aboard INTEGRAL (Knödlseder et al. 2005).

and radial velocity, in several historical galactic supernova remnants. These measurements will help clarify the ejection dynamics, including how common jets initiated by the core collapse are.

Wide-field gamma-ray instruments have shown the global diffuse emission from long-lived isotopes ^{26}Al and ^{60}Fe, illustrating clearly ongoing galactic nucleosynthesis. A necessary complement to these are high-sensitivity measurements of the yields of these isotopes from individual supernovae. A future European gamma-ray mission should determine these yields, and map the line emission across several nearby supernova remnants, shedding further light on the ejection dynamics. It is also likely that the nucleosynthesis of these isotopes in hydrostatic burning phases will be revealed by observations of individual nearby massive stars with high mass-loss rates.

For rare nearby supernovae, within a few Mpc, we will be given a glimpse of nucleosynthesis and dynamics from short-lived isotopes ^{56}Ni, and ^{57}Ni, as was the case for SN 1987A in the LMC. In that event we saw that a few percent of the core radioactivity was somehow transported to low-optical depth regions, perhaps surprising mostly receding from us, but there could be quite some variety, especially if jets or other extensive mixing mechanisms are ubiquitous.

4.4. Unveiling the origin of galactic positrons

The unprecedented imaging and spectroscopy capabilities of the spectrometer SPI aboard INTEGRAL have now provided for the first time an image of the distribution of 511 keV electron positron annihilation all over the sky (c.f. Fig. 6; Knödlseder et al. 2005). The outcome of this survey is astonishing: 511 keV line emission is only seen towards the bulge region of our Galaxy, while the rest of the sky remains surprisingly dark. Only a weak glim of 511 keV emission is perceptible from the disk of the Galaxy, much less as expected from stellar populations following the global mass distribution of the Galaxy. In other words, positron annihilation seems to be greatly enhanced in the bulge with respect to the disk of the Galaxy.

A detailed analysis of the 511 keV line shape measured by SPI has also provided interesting insights into the annihilation physics (Churazov et al. 2005). At least two components have been identified, indicating that positron annihilation takes place in a partially ionised medium. This clearly demonstrated that precise 511 keV line shape measurements provide important insights into the distribution of the various phases of the interstellar medium (ISM).

While INTEGRAL has set the global picture of galactic positron annihilation, high angular resolution mapping of the galactic bulge region is required to shed light on the still mysterious source of positrons. So far, no individual source of positron emission could have been identified, primarily due to the expected low levels of 511 keV line fluxes. An instrument with sufficiently good sensitivity and angular resolution should be able to pinpoint the origin of the positrons, by providing detailed maps of the central bulge region of the Galaxy. With additional fine spectroscopic capabilities, comparable to that achieved by the germanium detectors onboard the SPI telescope, the spatial variations of the 511 keV line shape will allow to draw an unprecedented picture of the distribution of the various ISM phases in the inner regions of our Galaxy.

Thus, with the next generation gamma-ray telescope, galactic positrons will be exploited as a messenger from the mysterious antimatter source in the Milky-Way, as well as a tracer to probe the conditions of the ISM that are difficultly to measure by other means.

5. Mission requirements

The major mission requirement for the future European gamma-ray mission is sensitivity. Many interesting scientific questions are in a domain where photons are rare (say 10^{-7} ph cm^{-2}s^{-1}), and therefore large collecting areas are needed to perform measurements in a reasonable amount of time. It is clear that a significant sensitivity leap is required, say 50–100 times more sensitive than current instruments, if the above listed scientific questions should be addressed.

With such a sensitivity leap, the expected number of observable sources would be large, implying the need for good angular resolution to avoid source confusion in crowded regions, such as for example the galactic centre. Also, it is desirable to have an angular resolution comparable to that at other wavebands, to allow for source identification and hence multi wavelength studies.

As mentioned previously, gamma-ray emission may be substantially polarised due to the non-thermal nature of the underlying emission processes. Studying not only the intensity but also the polarisation of the emission would add a new powerful scientific dimension to the observations. Such measurements would allow to discriminate between the different plausible emission processes at work, and would allow to constrain the geometry of the emission sites.

Taking all these considerations into account, the following mission requirements derive (c.f. Table 1). The energy band should cover the soft gamma-ray band, with coverage down to the hard X-ray band (to overlap with future X-ray observatories), and coverage of the major gamma-ray lines of astrophysical interest. A real sensitivity leap should be achieved, typical by a factor of 50–100 with respect to existing gamma-ray instrumentation. For high-resolution gamma-ray line spectroscopy a good energy resolution is desirable to exploit the full potential of line profile studies. A reasonably sized field-of-view together with arcmin angular resolution should allow the imaging of field populations of gamma-ray sources in a single observation. Finally, good polarisation capabilities, at the percent level for strong sources, are required to exploit this additional observable.

Table 1. Mission requirements for the future European gamma-ray mission (sensitivities are for 10^6 seconds at 3σ detection significance).

Parameter	Requirement
Energy band	50 keV – 2 MeV
Continuum sensitivity	10^{-8} ph cm^{-2}s^{-1}keV^{-1}
Narrow line sensitivity	5×10^{-7} ph cm^{-2}s^{-1}
Energy resolution	2 keV at 600 keV
Field of view	30 arcmin
Angular resolution	arcmin
Polarisation	1% at 10 mCrab

Can these mission requirements be reached within the 2015–2025 time frame? We are convinced that the answer is yes. How can these mission requirements be reached? We think that the best solution is the implementation of a broad-band gamma-ray lens telescope based on the principle of Laue diffraction of gamma-rays in mosaic crystals. In the following section we explain why we come to this conclusion, and how such a future gamma-ray telescope for Europe may look like.

6. A future gamma-ray telescope for Europe

The sensitivity of current gamma-ray telescopes is severely limited by the internal instrumental background and the size of the photon collecting area. The instrumental background arises from the cosmic-ray bombardment of the telescope (and in particular with the gamma-ray detector material) and the material around, and scales to first order with detector volume.[1] For a given detector thickness, the instrumental background is therefore proportional to the geometrical detector area, $C_{\rm B} \propto A_{\rm det}$. The received signal scales proportionally to the collecting area, $S \propto A_{\rm coll}$, and thus, the signal-to-noise ratio scales (assuming background domination) as

$$S/N \approx \frac{S}{\sqrt{C_{\rm B}}} \propto \frac{A_{\rm coll}}{\sqrt{A_{\rm det}}} \tag{1}$$

For conventional gamma-ray telescopes, such as the SPI and IBIS instruments aboard INTEGRAL, the detector area is identical to the collecting area, i.e. $A_{\rm det} = A_{\rm coll}$, and therefore the signal-to-noise ratio scales as $S/N \propto \sqrt{A_{\rm coll}}$. Therefore, if one would aim in increasing the INTEGRAL sensitivity by one order of magnitude, an instrument a hundred times bigger would be needed. It is obvious that it is unrealistic to follow this way. With INTEGRAL, the technique used for conventional gamma-ray telescope has probably reached its climax.

Decoupling the collecting area from the detection area, however, can change the situation dramatically. For a collecting area comparable to that of the IBIS detector ISGRI and a detection area as small as 1 cm^2, a sensitivity gain of approximately a factor of ~ 50 would be achieved. This would however mean that gamma-rays need to be focused or concentrated by a large area collector onto a small area detector, a technique that was for a long time believed to be inaccessible to gamma-ray astronomy.

Technological developments undertaken by several groups in Europe during the last years have now demonstrated that gamma-ray focusing is indeed possible (Halloin et al. 2004; De Chiara et al. 2000). The focusing is achieved by organising crystals onto rings or in an Archimedes spiral around the optical axis, making use of small angle Bragg reflection in Laue geometry to deviate the incoming radiation onto a small focal spot. Broad band energy coverage is achieved by using mosaic crystals with varying inclinations and radial distances to the optical axis (von Ballmoos et al. 2004; Frontera et al., these proceedings; von Ballmoos et al., these proceedings). The gamma-ray lens principle has been demonstrated by various laboratory measurements, and also, during a successful balloon flight of the CLAIRE prototype telescope which led to the first ever detection of a gamma-ray source (the Crab nebula) by a focusing gamma-ray telescope (Halloin et al. 2004).

The small diffraction angles of typically few tens of arcmin together with reasonable ring radii of the order of one meter or more, lead to substantial focal lengths of at least a few tens of meters, making it difficult to place the lens on the same satellite as the detector. Thus, a formation flight scenario comprising a lens spacecraft together with a detector spacecraft seems the most plausible configuration for such an instrument. We note that such a gamma-ray lens telescope is currently under study at the French

[1] For energies $\lesssim 100$ keV a large fraction of the background is of astrophysical nature and arises from the isotropic cosmic gamma-ray background. Therefore, the background at these energies depends crucially on the solid angle covered by the field of view of the instrument.

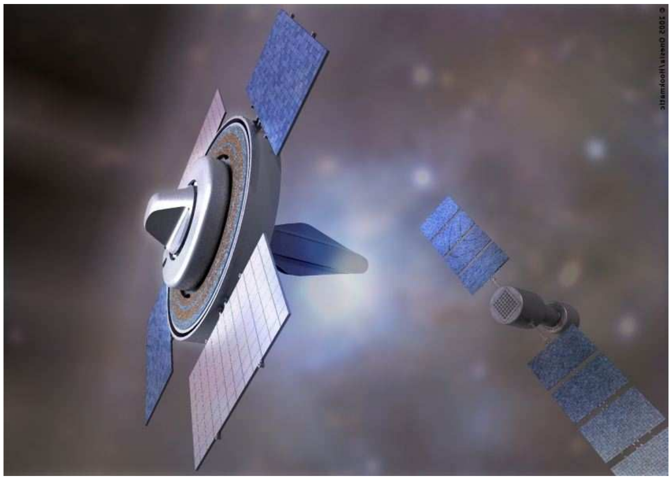

Figure 7. Artists view of the future European gamma-ray telescope. A Laue lens, situated on the left spacecraft, is focusing gamma-rays onto a small detector, situated on the right spacecraft. Both spacecrafts are in formation flight with a typical focal length between a few tens and a few hundreds metres.

space agency CNES (project MAX; von Ballmoos et al. 2004) and at the ESA Science Payload & Advanced Concepts Office (project Gamma-Ray Lens), which both confirm the feasibility of such a scenario. We therefore believe that a gamma-ray lens telescope in formation flight configuration provides the most promising instrumental concept allowing advances in the field of space-based gamma-ray astronomy.

The precise design of the gamma-ray lens telescope is currently under discussion in a dedicated working group. The artists view in Fig. 7 may, however, give an idea how the future European gamma-ray telescope could look like. In this example, the lens spacecraft is composed of concentric rings of crystals, where each ring is focusing a specific narrow energy band on the (same) focal spot on the detector spacecraft. Higher energies show smaller diffraction angles and therefore are situated closer to the optical axis (inner rings). Conversely, lower energies show larger diffraction angles and therefore are situated on the outer rings. The lowest energies may require radial distances from the optical axis that exceed the available space in launcher fairings, therefore deployable lens petals may eventually be employed.

7. Conclusions

The gamma-ray band presents a unique astronomical window that allows the study of the most energetic and most violent phenomena in our Universe. With ESA's INTEGRAL observatory, an unprecedented global survey of the soft gamma-ray sky is currently performed, revealing hundreds of sources of different kinds, new classes of objects, extraordinary views of antimatter annihilation in our Galaxy, and fingerprints of recent nucleosynthesis processes. While INTEGRAL provides the longly awaited global overview over the soft gamma-ray sky, there is a growing need to perform deeper, more focused investigations of gamma-ray sources, comparable to the step that has been taken in X-rays by going from the ROSAT survey satellite to the more focused XMM-Newton observatory. Technological advances in the past years in the domain of gamma-ray focusing using Laue diffraction techniques have paved the way towards a future European gamma-ray mission, that will outreach past missions by large factors in sensitivity and angular resolution. Such a future *Gamma-Ray Imager* will allow to study particle acceleration processes and explosion physics in unprecedented depth, providing essential clues on the intimate nature of the most violent and most energetic processes in the Universe.

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