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GRI: THE GAMMA-RAY IMAGER MISSION

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Abstract.
With the INTEGRAL observatory, ESA has provided a unique tool to the astronomical community revealing hundreds of sources, new classes of objects, extraordinary views of antimatter annihilation in our Galaxy, and fingerprints of recent nucleosynthesis processes. While INTEGRAL provides the global overview over the soft gamma-ray sky, there is a growing need to perform deeper, more focused investigations of gamma-ray sources. In soft X-rays a comparable step was taken going from the Einstein and the EXOSAT satellites to the Chandra and XMM/Newton observatories. Technological advances in the past years in the domain of gamma-ray focusing using Laue diffraction have paved the way towards a new gamma-ray mission, providing major improvements regarding sensitivity and angular resolution. Such a future Gamma-Ray Imager will allow the study of particle acceleration processes and explosion physics in unprecedented detail, providing essential clues on the innermost nature of the most violent and most energetic processes in the Universe.

1 From INTEGRAL to GRI

Following 4 years of successful operations, INTEGRAL has significantly changed our vision of the gamma-ray sky. The telescopes aboard the satellite have revealed hundreds of sources of different types, new classes of objects, extraordinary and puzzling views of antimatter annihilation in our Galaxy, and fingerprints or recent nucleosynthesis processes. With the wide fields of view of the IBIS and SPI telescopes, INTEGRAL is an exploratory-type mission that allows extensive surveys of the hard X-ray and soft gamma-ray sky, providing a census of the source populations and first-ever allsky maps in this interesting energy range. The good health of the instruments allows to continue the exploration during the upcoming years, enabling INTEGRAL to provide the most complete and detailed survey ever, which will be a landmark for the discipline throughout the next decades.

Based on the INTEGRAL discoveries and achievements, there is now a growing need to perform more focused studies of the observed phenomena. High-sensitivity investigations of point sources, such as compact objects, pulsars, and active galactic nuclei, should help to uncover their yet poorly understood emission mechanisms. A deep survey of the galactic bulge region with sufficiently high-angular resolution should shed light on the still mysterious source of positrons. And a sensitivity leap in the domain of gamma-ray lines should allow the detection of nucleosynthesis products in individual supernova events, providing direct insights into the physics of the exploding stars.

Technological advances in the past years in the domain of gamma-ray focusing using Laue diffraction have paved the way towards a new gamma-ray mission that can fulfil these requirements. Laboratory work and balloon campaigns have provided the proof-of-principle for using Laue lenses as focusing devices in gamma-ray telescopes (von Ballmoos et al. 2004; Halloin et al. 2004), and concept studies by CNES and ESA have demonstrated that such an instrument is technically feasible and affordable (Duchon et al. 2006; Brown 2005). Complemented by a hard X-ray telescope, either based on a coded mask or a multilayer mirror, a broad-band energy coverage can be achieved that allows detailed studies of astrophysical sources at unprecedented sensitivity and angular resolution, from a few tens of keV up to at least 1 MeV.

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Bringing our scientific requirements into the context of these technological achievements, we started a common effort to define the scenario for a future gamma-ray mission that we baptised the *Gamma-Ray Imager* (GRI). The GRI mission fits well into the framework of ESA's Cosmic Vision 2015-2025 planning, and it will provide a perfect successor for INTEGRAL in that it will considerably deepen the study of the phenomena unveiled by the observatory.

2 Science objectives

The science objectives of GRI can be summarised into two major themes: (1) understanding the nature and physics of cosmic explosion processes and (2) the study and understanding of cosmic particle accelerators. In particular, with GRI we want to

- understand how Type Ia supernova explode by studying the gamma-ray line profiles and lightcurves produced by the radioactive decay of explosion products
- investigate how core-collapse can drive supernova explosions by measuring the various radioactive isotopes that emerge from these events
- unveil the galactic source of positrons by high-resolution imaging of the galactic bulge region and 511 keV line observations of candidate sources
- discover nucleosynthesis products during nova outbursts to better understand their physics and explosion conditions
- learn how galactic compact objects accelerate matter by investigating emission components during state transitions and by determining the composition of emerging jets using spectral signatures
- identify the nature of the hard emission tails discovered by INTEGRAL in Anomalous X-ray Pulsars and Soft Gamma-Ray Repeaters by performing precise measurements of their spectral shapes
- settle the question on the origin of the extragalactic soft gamma-ray background by precise measurements of the spectral energy distributions of AGNs and by resolving the diffuse emission into individual sources
- perform multi-wavelength studies of galactic source populations revealed in adjacent energy bands, and in particular at GeV-TeV energies by GLAST, HESS & MAGIC, to constrain the nature of the accelerated particles
- probe particle acceleration in solar flares by performing spectro-imaging of active regions studying the development of the radioactive patch after the outburst

3 The GRI mission

3.1 Mission requirements

The GRI mission requirements that we derived from our scientific goals are summarised in Table 1. Our major requirement for GRI is sensitivity. Many interesting scientific questions are in a domain where photons are rare, and therefore large collecting areas are needed to perform measurements in a reasonable amount of time. Our continuum and line sensitivity requirements correspond to a factor of $\sim$30 improvement with respect to IBIS and SPI, allowing for ten times deeper studies within ten times less observing time.

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.

Gamma-ray emission may be substantially polarized due to the non-thermal nature of the underlying emission processes. Studying not only the intensity and the spectrum but also the polarization of the emission would add a new powerful scientific dimension to the observations. Such measurements would allow the discrimination between the different plausible emission processes at work, and would constrain the geometry of the emission sites.

Table 1. GRI mission requirements (sensitivities are for 100 ks and a detection significance of 3σ).

Parameter	Requirement	Goal
Energy band (keV)	50 – 900	50 - 1300
Continuum sensitivity (ph $cm^{-2}s^{-1}keV^{-1}$)	10^{-7}	3×10^{-8}
Narrow line sensitivity (ph $cm^{-2}s^{-1}$)	3×10^{-6}	10^{-6}
Energy resolution	3%	0.5%
Field of view (arcmin)	5	10
Angular resolution (arcsec)	60	30
Time resolution (μs)	100	100
Polarization MDP (for 10 mCrab in 100 ks)	5%	1%

3.2 GRI design

The key element of GRI is a broad-band gamma-ray lens based on the principle of Laue diffraction of photons in mosaic crystals. Each crystal can be considered as a little mirror which deviates γ-rays through Bragg reflection from the incident beam onto a focal spot. Although the Bragg relation holds only for one specific energy E and its multiples, the mosaic spread $\Delta\theta$ that occurs in the crystal leads to an energy spread $\Delta E \propto \Delta\theta E^2$. Placing the crystals on concentric rings around an optical axis, and careful selection of the inclination angle for each of the rings, allows then the building of a broad-band gamma-ray lens that has continuous energy coverage over a specified band. Since larger energies E imply smaller diffraction angles θ, crystals diffracting large energies are located on the inner rings of the lens. Conversely, smaller energies E are diffracted by crystals located on the outer rings.

Several considerations lead us to consider a minimum energy of $\sim$200 keV for the Laue lens. Below this energy, the band pass for individual crystals becomes very small, requiring an enormous number of crystal tiles to provide a continuum energy coverage. In addition, machining constraints will probably not allow the use of crystals that are thinner than $\sim$1–2 mm, hence for energies below $\sim$200 keV, absorption of γ-rays starts to reduce the efficiency of the lens.

The upper energy of the Laue lens is basically set by the focal length of the telescope and the smallest radius that can be covered with crystal tiles. Mosaic defocusing, i.e. the spread of the focused gamma-ray beam due to the mosaicity of the crystals, becomes important for focal lengths exceeding $\sim$100 metres, reducing the sensitivity gain of the instrument. In addition, for a given energy, the radius on which a given crystal has to be placed to focus on the focal spot increases linearly with the focal length. Thus, the minimum energy of the Laue lens drives the total lens diameter. Fixing the minimum energy at $\sim$200 keV and the lens diameter at $\lesssim$4 metres, results in a focal length of 60–80 m and a maximum energy of $\sim$1 MeV.

The most promising technology for realizing such a long focal length is formation flying of two satellites, one carrying the lens and the other the detector. The focal distance has to be kept to within $\pm$10 cm in order to maintain the optimum performances of the instrument. The size of the focal spot is primarily determined by the size of the crystal tiles (between 1×1 cm^2 and 2×2 cm^2) and the mosaic spread $\Delta\theta$ of the crystals (1 arcmin at a distance of 100 m corresponds to a size of 3 cm). Thus the maximum allowed lateral displacement of the detector spacecraft with respect to the lens optical axis will be of the order of $\pm$1 cm. Considering the pointing precision, an accuracy of $\sim$ 15 arcsec are sufficient to maintain the system aligned on the source.

Crystals that we currently have under consideration are copper and germanium. Germanium has been employed for the CLAIRE balloon lens (von Ballmoos et al. 2004), while copper crystals have been produced and tested at ILL (Grenoble). We are also studying the possibility of using gradient or bent crystals with the aim of substantially increasing the diffraction efficiencies (Barrière et al. 2006). Another possibility is the use of silver or gold crystals, which provide good diffraction efficiencies at much less weight than copper.

Although the lens is basically a radiation concentrator (with a beam size that corresponds to the crystal mosaicity, say $\sim$ 1 arcmin), it has a substantial off-axis response. For sources situated off the optical axis, the focal spot will turn into a ring-like structure (which is centred on the lens optical axis), with an azimuthal modulation that reflects the azimuthal angle of the incident photons. Thus, the arrival direction of off-axis photons can be reconstructed from the distribution of the recorded events on the detector plane. The field-of-view of the lens is therefore basically restricted by the size of the detector. For a detector size of 30×30 cm^2 and a focal length of 100 m the field-of-view amounts to $\sim$15 arcmin. Within this field-of-view the lens can be used as an (indirect) imaging device.

It is important to notice that a Laue lens will not significantly alter the polarization of the incident radiation. In other words, a polarized gamma-ray beam will still be polarized after concentration on the focal spot, and the use of a polarization sensitive detector will allow for polarization measurements. In view of the expected polarization of non-thermal emission, this aspect of GRI opens a new discovery space which will considerably improve our understanding of the observed objects.

To profit to the full from the gamma-ray lens, we employ a position sensitive detector in the focal spot. Our actual design studies are mainly focused on a pixelised stack of detector layers, which on the one hand has the required position sensitivity, and on the other hand can be exploited as Compton telescope for instrumental background reduction. Possible detector materials under investigation are CdTe, CZT, Si, and/or Ge (Caroli et al. 2006; Wunderer et al. 2006). Although Germanium would provide the best energy resolution (and is certainly the preferred option for detailed studies of gamma-ray lines), the related cooling and annealing requirements may drives us towards other options.

The usage of a pixelised detector stack has the nice side effect that it can be employed as an all-sky monitor for soft gamma-ray emission (Wunderer et al. 2006). If used as a Compton telescope, the detector will be sensitive to any direction of the sky that is not shielded by the satellite, providing thus an onboard capability to detect variable or transient sources. Since we cannot predict if an all-sky monitor will be available by the time that GRI will operate, we think that an all-sky monitoring capability aboard GRI itself is important to quickly react to targets of opportunity. We are currently investigating the technical details of such a solution.

In order to extend the GRI energy coverage towards energies below $\sim$200 keV we plan to add a hard X-ray telescope to the mission. Such a broad-band coverage is crucial for the understanding of compact objects physics, since such sources exhibit generally temporal spectral variations over a wide energy band. In particular, the accurate determination of energy cut-offs will rely on an accurate determination of the broad-band spectrum of the object under investigation. As baseline we propose to use a collimated coded-mask telescope for this purpose. At energies $\lesssim$200 keV the cosmic background radiation presents an important source of photons, limiting severely the sensitivity of current wide field-of-view coded mask telescopes, such as IBIS on INTEGRAL or the BAT on SWIFT. Collimation considerably reduces this background component, promising an interesting sensitivity increase at these low energies. Increasing the size of the detectors with respect to ISGRI will also help to improve the efficiency at higher energies (Natalucci et al. 2006)

Alternatively, we study the possibility of using a single-reflection multilayer-coated mirror telescope to cover the hard X-ray band. Theoretically, such a solution promises an excellent sensitivity for hard X-ray energies, yet it is unclear up to which energies these capacities may be extended. The american NuStar mission or the French-Italian Simbol-X mission plan to use mirrors up to energies of $\sim$80 keV. Potentially, even higher energies may be reached (Christensen et al. 2006).

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