GRI: the Gamma-Ray Imager mission

Jürgen Knödlseder\textsuperscript{a} (on behalf of the GRI consortium\textsuperscript{b})

\textsuperscript{a}Centre d’Etude Spatiale des Rayonnements, 9, avenue du Colonel-Roche, 31028 Toulouse, France;

\textsuperscript{b} APC (France), Argonne National Laboratory (United States), CESR (France), CNM (Spain), Copernicus Astronomical Center (Poland), CSNSM (France), DNSC (Denmark), IAP (France), IEEC/CSIC (Spain), INAF Brera (Italy), IFAE (Spain), INAF-IASF Bologna (Italy), INAF-IASF Milano (Italy), INAF-IASF Palermo (Italy), INAF-IASF Roma (Italy), INAF-OAR (Italy), IOFFE (Russia), ILL (France), LAM (France), MPE (Germany), Mullard Space Science Laboratory (United Kingdom), SINP, MSU (Russia), SRON (The Netherlands), SSL Berkeley (United States), Univ. of Coimbra (Portugal), Univ. of Ferrara (Italy), Univ. of Southampton (United Kingdom), Univ. of Utrecht (The Netherlands)

ABSTRACT

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. Here particles are accelerated to extreme relativistic energies by mechanisms which are still poorly understood, and nuclear reactions are synthesizing the basic constituents of our world. Cosmic accelerators and cosmic explosions are the major science themes that are addressed in the gamma-ray regime.

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 and multilayer-coated mirror techniques have paved the way towards a gamma-ray mission, providing major improvements compared to past missions regarding sensitivity and angular resolution. Such a future Gamma-Ray Imager will allow to study 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.

Keywords: gamma-ray astronomy, mission concepts, crystal lens telescope

1. WHY GAMMA-RAY ASTRONOMY?

As introductory remark, it is worth emphasizing 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 background radiation. Cosmic acceleration takes place on all scales: locally in solar flares, within our Galaxy (e.g. in compact binaries, pulsars and 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.

2. COSMIC ACCELERATORS

2.1. 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 microquasars, 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 polarization 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.

2.2. 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\(^\text{19}\) (see left panel of Fig. 1).

At higher energies, say above \(\sim 300\) keV, the situation is less clear. In this domain, only a small fraction 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 (see right panel of Fig. 1). While below $\sim 300$ 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 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. Searching for the hard powerlaw emission tails in these objects is therefore a key objective for a future gamma-ray mission.

2.3. The origin of the soft $\gamma$-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. Below 8 keV about $\gtrsim 80\%$ of the emission has been resolved into individual sources, which have been identified as active galactic nuclei (AGN). Above 8 keV, however, only $\lesssim 50\%$ of the CXB has been resolved into sources, while in the 20 – 100 keV hard X-ray band, where IBIS is most sensitive, only $\sim 1\%$ of the emission has been resolved. Above this energy, in the soft $\gamma$-ray band, basically nothing is known about the nature of the cosmic background radiation.

While the situation in the hard X-ray band ($\lesssim 100$ keV) may change after the launch of the Simbol-X telescope (see contribution of P. Ferrando, these proceedings), the soft $\gamma$-ray band remains unexplored. It is however this energy band which may provide the key for the understanding of the cosmic background radiation. Synthesis models, which are well established and tested against observational results, can be used to evaluate the integrated AGN contribution to the soft $\gamma$-ray background. However, the spectral shape of the different classes of AGN that are used for modelling the background has so far not been firmly established at soft $\gamma$-ray energies. As an illustration, Fig. 2 shows the impact of the AGN power law cut-off energy on the resulting prediction of the cosmic background radiation. Observations by BeppoSAX 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. 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
Figure 2. The 0.25 – 400 keV cosmic background spectrum fitted with synthesis models. None of the models provides a satisfactory fit of the observations.

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.

Therefore, the goal of GRI is to measure the soft γ-ray Spectra Energy Distribution (SED) 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.

2.4. 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, 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 isolated pulsars, accretion powered pulsars, occurring in low-mass or high-mass binary systems, like spin-up/spin-down and millisecond pulsars, and magnetically powered pulsars, known as magnetars.

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 enable 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.\textsuperscript{17, 18} In fact, above $\sim 10$ keV a dramatic upturn is observed in the spectra which is expected to cumulate in the 100 keV – 1 MeV domain (see 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\textsuperscript{24} (c.f. Fig. 3). The process that gives rise to the observed gamma-ray emission is 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 polarization is expected for the high-energy emission from these exotic objects, and polarization measurements may be 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.

2.5. Particle acceleration in low B-fields

The possibility to have high energy emission from cosmic sources in the range above 0.1 – 1 TeV has been argued in the last 20 years. Recently, HESS (High Energy Stereoscopic System), a ground-based Cerenkov array telescope has become fully operational and has performed the first Galactic plane scan with a sensitivity of a few percent of the Crab at energies above 100 GeV. This survey revealed the existence of a population of fourteen TeV objects, most of which previously unknown.\textsuperscript{1, 2} More recently, the MAGIC (Major Atmospheric Gamma Imaging Cerenkov telescope) collaboration has reported a positive observations of HESS J1813-178, resulting in
a gamma-ray flux consistent with the previous HESS detection and showing a hard power law with $\Gamma = 2.1$ in the range from $0.4 - 10$ TeV.\textsuperscript{3} These findings have an important astrophysical implication for the understanding of cosmic particle accelerators via gamma ray measurements in order to disentangle the mechanisms active in the different emitting regions and, in turn, to understand the nature of the sources. In fact, the detection of a substantial number of very high energy Galactic sources emitting a large fraction of energy in the GeV to TeV range has opened a new space window for astrophysical studies related to cosmic particle accelerators. Different types of galactic sources are known to be cosmic particle accelerators and potential sources of high energy gamma rays: isolated pulsars and their pulsar wind nebulae (PWN), supernova remnants (SNR), star forming regions, and binary systems with a collapsed object like a microquasar or a pulsar.

So far, out of the HESS sources without any known counterpart only for two of them, namely HESS J1813-178 and HESS J1837-067, hard X-ray and soft gamma-ray emission has been detected, supporting the Synchrotron Inverse Compton scenario.\textsuperscript{21, 28} Unfortunately, further attempts to model in detail the broad band emission from these two objects\textsuperscript{3, 5} have not been completely successful\textsuperscript{29} as shown in Fig. 4. In this scenario, the lack of radio/X-ray emission in most of those HESS sources is particularly interesting since it strongly suggests that the accelerated particles may be nucleons rather than high energy electrons.

It is clear that both the hadronic and leptonic models so far proposed fail to easily explain the whole observational picture if the radio, hard X-ray, soft gamma-ray and TeV high energy photons are produced in the same SNR region by a single physical process. In fact, to firmly confirm the above hypothesis it is necessary to have instruments capable to provide arcsec spatially resolved spectroscopy, not possible with the present generation of gamma-ray instruments.

This can be achievable with a new generation of Gamma Ray Imagers if capable to provide at the same time high angular resolution coupled with 10 time better sensitivity.
3. COSMIC EXPLOSIONS

3.1. 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 sufficient mass accretion that would push the white dwarf over its stability limit.\(^{13}\) 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.\(^{20}\) 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.\(^{13}\)

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: the accelerating expansion of the Universe.\(^{26}\) Although empirical corrections to the observed optical lightcurves seem to allow for some kind of standardization, there is increasing evidence that Type Ia supernovae is not an homogeneous class of objects.\(^{22}\)

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 that 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 information 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.

3.2. 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 positron-electron annihilation all over the sky (c.f. Fig. 6). 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 glimmer of 511 keV emission is perceptible from the disk of the Galaxy, much less than 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. At least two components have been identified, indicating that positron annihilation takes place in a partially ionized 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 difficult to measure by other means.

### 3.3. 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 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 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.

### 3.4. Nova nucleosynthesis

Classical novae are another site of explosive nucleosynthesis that is still only partially understood. 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 $\beta^+$-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. THE GRI MISSION

#### 4.1. 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 $10^{-8}$ ph cm$^{-2}$s$^{-1}$keV$^{-1}$), 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 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 to discriminate between the different plausible emission processes at work, and would 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 soft gamma-rays, with an extension down to the hard X-ray band to allow the study of broad-band spectra. At the same time, major gamma-ray lines of astrophysical interest (i.e. 511 keV and 847 keV) should be accessible. We therefore set our baseline energy range to 50–2000 keV.

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 polarization 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 3\(\sigma\) detection significance).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy band</td>
<td>50 keV – 2 MeV</td>
</tr>
<tr>
<td>Continuum sensitivity</td>
<td>(10^{-8}) ph cm(^{-2}) s(^{-1}) keV(^{-1})</td>
</tr>
<tr>
<td>Narrow line sensitivity</td>
<td>(5 \times 10^{-7}) ph cm(^{-2}) s(^{-1})</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>2 keV at 600 keV</td>
</tr>
<tr>
<td>Field of view</td>
<td>15 arcmin</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>arcmin</td>
</tr>
<tr>
<td>Polarization</td>
<td>1% at 10 mCrab</td>
</tr>
</tbody>
</table>

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.\(^8\,\,10\,\,30\) The Laue lens may eventually be complemented by a coded mask telescope or a multilayer-coated mirror telescope in order to achieve coverage in the hard X-ray domain. In addition, the lens detector may be designed in a Compton configuration so that it could be simultaneously used as an all-sky monitor.

### 4.2. 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 (von Ballmoos and Frontera et al., these proceedings). Each crystal can be considered as a little mirror which deviates \(\gamma\)-rays through Bragg reflection from the incident beam onto a focal spot. Although the Bragg relation

\[
2d \sin \theta = n \frac{hc}{E}
\]  

(1)
implies that only a single energy \( E \) (and its multiples) can be diffracted by a given crystal, the mosaic spread \( \Delta \theta \)
that occurs in each crystal leads to an energy spread \( \Delta E \propto \Theta E^2 \) (\( d \) is the crystal lattice spacing, \( \theta \) the Bragg angle, \( n \) the diffraction order, \( h \) the Planck constant, \( c \) the speed of light and \( E \) the energy of the incident photon). Placing the crystals on concentric rings around an optical axis, and the careful selection of the inclination angle on each of the rings, allows then to build a broad-band gamma-ray lens that has continuous energy coverage over a specified band. Since larger energies \( E \) imply smaller gamma-ray lens that has continuous energy coverage over a specified band. Since larger energies \( E \) imply smaller diffraction angles \( \theta \) (see Eq. 1), crystals diffracting large energies are located on the inner rings of the lens. Conversely, smaller energies \( E \) imply larger diffraction angles and consequently are located on the outer rings.

A Laue lens starts to become efficient from energies on where photon absorption becomes small within the crystals. For copper crystals and a minimum machinable crystal thickness of \( 1 \) – \( 2 \) mm this energy is situated around \( E_{\text{min}} \approx 100 \) keV. To cover a continuous energy band, the crystal energy bandpass \( \Delta E \) should not be too small. Since \( \Delta E \propto E^2 \), the number of required crystal tiles increases considerably with decreasing energy, leading to a natural lower energy boundary (also situated around \( \sim 100 \) keV) where Bragg reflection becomes inappropriate for photon concentration.

Having these considerations in mind, we propose a broad-band Laue lens covering the energy band \( \approx 150 \) keV – \( 2 \) MeV as the central element of GRI. The lens is composed of a ring with inner and outer diameters of \( \sim 1 \) m and \( \sim 3.8 \) m, respectively, resulting in \( \sim 10 \) m\(^2\) of geometrical lens area. Eventually, deployable lens petals may be added to reach even lower energies, and we actually are studying the technical feasibility of such a solution (Frontera et al., these proceedings). Owing to the small scatters of \( \sim 0.1^\circ \) – \( 1^\circ \) (for the largest and smallest energies, respectively), the focal spot of the lens will be situated around \( f \approx 100 \) m behind the lens. This implies that the detector which collects the concentrated gamma-rays will be situated on a second spacecraft. Both spacecrafts fly in formation, but the precision constrains on the formation are not very severe. Due to the small Bragg angles, the focal distance has only to be kept 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 (situated between \( 1 \times 1 \) cm\(^2\) and \( 2 \times 2 \) 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.

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 \( 30 \times 30 \) 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 (indirect) imaging device. The imaging performances are considerably improved by employing a dithering technique, similar to that employed for INTEGRAL.

It is important to notice that the small angle crystal diffraction that is exploited for gamma-ray focusing does not 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 (Caroli et al., these proceedings). 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 take maximum profit of 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. and Wunderer et al., these proceedings). 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 drive us towards other options.
The detector configuration we propose (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., these proceedings). 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 currently investigate technical details of such a solution.

In order to extend the GRI energy coverage towards lower energies (below \( \approx 150 \) keV) we also investigate the possibility to add a hard X-ray monitor to the mission. Such a broad-band coverage would be crucial to better understand the physics of compact objects, which exhibit 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. Two options are currently considered: a small multilayer-coated mirror telescope or a collimated coded mask telescope (Natalucci, these proceedings).

Theoretically, a multilayer-coated mirror promises an excellent sensitivity for hard X-ray astronomy, 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 (e.g. Christensen, these proceedings). Alternatively, a collimated coded mask telescope may provide a good option for a hard X-ray monitor on GRI. At energies \( \lesssim 100 \) keV the cosmic background radiation presents the most 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 reduced this background component, promising an interesting sensitivity increase at these low energies.

We currently investigate the accommodation of a multilayer-coated mirror or a coded mask telescope on GRI. The mirror could be inserted within the spare area (\( \sim 1 \) m diameter) inwards of the innermost crystal rings or in some specific area reserved on the lens area. Analogously, the coded mask could have a ring-like shape, and could be fit within the innermost crystal rings (Natalucci, these proceedings).

5. 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 EINSTEIN 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 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.

REFERENCES

29. Ubertini et al., 2006, Experimental Astronomy, in press