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Soft gamma-ray polarimetry using a Laue lens telescope: The Gamma Ray Imager

Nicolas Barrière*, **Lorenzo Natalucci and Pietro Ubertini**
INAF/IASF Rome - Italy
E-mail: `nicolas.barriere{at}iasf-roma.inaf.it`

The Gamma Ray Imager (GRI) mission is a concept that was elaborated by a large international consortium and proposed to ESA in the framework of the Cosmic Vision first announcement of opportunity in 2007. The aim was simple: to beat the instrumental background in order to get a sensitivity improvement of at least one order of magnitude with respect to existing instruments in the very difficult hard X-ray / soft gamma domain. The result of this study was a design for a focusing telescope based on innovative optics, depth-graded multilayer mirrors to cover the energy range from 20 to 250 keV and a Laue lens to take over from 220 keV up to 1.3 MeV. GRI's estimated performance is a continuum sensitivity ($\Delta E = E/2$) better than 10^{-7} ph/s/cm^2/keV for 100 ks exposure time and an angular resolution of the order of 30 arcsec in a 5 arcmin field of view. In this paper, we go further in the study of the concept, demonstrating that the Laue lens is fully transparent to polarization, making the telescope a perfect instrument for polarimetric studies since the focal plane is an assembly of finely pixelated detector planes, ideal to perform Compton scattering polarimetry.

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*Speaker.

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1. Introduction

The use of Laue lenses is an emerging technique based on diffraction in crystals that allows the concentration of soft gamma rays. Practically the method can be applied efficiently between about 100 keV and 1.5 MeV. In astrophysics this kind of optics could lead to the gain of one - or even two - orders of magnitude in sensitivity over existing instruments: knowing that the instrumental background count rate in detectors is roughly proportional to their volume, the decoupling of the collecting area from the sensitive area allows a dramatic increase of the signal to background ratio and hence enables an unprecedented sensitivity to be reached.

The Gamma Ray Imager (GRI) mission concept has been elaborated by a consortium comprising a large international community and was proposed to ESA in 2007 as an answer to the first announcement of opportunity of the Cosmic Vision plan [1]. It proposes to cover energies from 20 keV up to 1.3 MeV with unequaled sensitivity, using single reflection depth-graded multilayer mirrors for the low energy (up to 250 keV) [2], and a Laue lens from 220 keV up to 1.3 MeV [3]. The focal length of both focusing optics equals 100 m implying two formation flying satellites with optics carried by one, and the focal plane carried by the other. Both optics are co-axial and focus on a common detector which is composed of a stack of finely pixelated CZT planes [4] in order to take advantage of the imaging capabilities of the optics and to be sensitive to the polarization of the focused radiation. The estimated continuum sensitivity is better than 10^{-7} ph/cm^2/s/ keV for a 100 ks exposure; the narrow line sensitivity is better than 3 x 10^{-6} ph/cm^2/s for the same integration time (Figure 1). GRI can achieve an angular resolution of $\sim$ 30 arcsec within a field of view of 5 arcmin - which represents an important achievement in the gamma-ray domain.

In this paper the accent is put on the inherent polarimetry capability that a Laue lens telescope presents. The next section describes the main science topic that can be addressed by such a telescope. The third section introduces the Laue lens principle and shows its current development status. The fourth section deals with the transmission of polarized radiation through Laue lenses, and emphasizes why such instrument is perfectly suited to perform polarimetric studies.

2. Science motivations

Based on INTEGRAL and SWIFT [6, 7] discoveries and achievements, there is now a growing need to perform more focused studies of the observed phenomena. Featuring high sensitivity and high angular resolution, a GRI-class Laue lens telescope is perfectly adapted to further our understanding of high energy processes occurring in a variety of violent events. High sensitivity investigations of point sources such as compact objects, pulsars and galactic nuclei should bring important insights into the still poorly understood emission mechanisms. For this purpose the polarization detection capabilities inherent to a Laue lens telescope in conjunction with its high angular resolution would be extremely helpful, for instance to distinguish between various models of pulsars magnetosphere. Also the link between jet ejection and accretion in black hole and neutron star systems could be clarified by observation of the spectral properties and polarization of the transition state emission.

High sensitivity observations would also be precious for gamma-ray lines such as that emitted during novae (^{7}Li at 478 keV) and Type Ia supernovae (^{56}Co at 812 keV and 847 keV) to under-

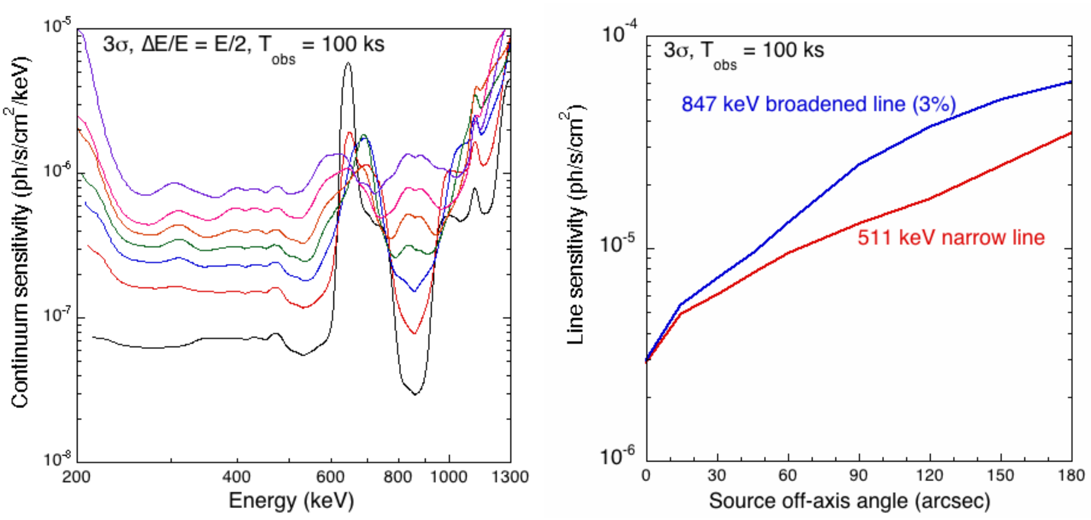


Figure 1: GRI's continuum *(left)* and line sensitivity *(right)* for a point source. Evolution of the sensitivity is shown for the following values of the source off-axis angle: 0", 30", 60", 90", 120", 150" and 180"

stand the explosion mechanisms and study nucleosynthesis. Observation of light curves and line shape evolution will permit to tighter constraints on physical parameters allowing the discrimination among the numerous models describing these events. A Laue lens telescope can also greatly help to solve the mystery of the galactic positrons origin. Through the observation of the e^+-e^- annihililation line at 511 keV, pointed observations on a selection of compact objects such as low mass X-ray binaries would bring important constraints on the origin of the emission and eventually on positron production rate.

3. Laue lens principle and state of the art

A Laue lens concentrates gamma-rays using Bragg diffraction in the volume of a large number of crystals arranged in concentric rings and accurately orientated in order to diffract radiation coming from infinity towards a common focus (e.g. [8]). In the simplest design each ring is composed of identical crystals, their axis of symmetry defining the line of sight of the lens. Bragg's law, $2d_{hkl}\sin\theta_B = n\lambda$, links the ray angle of incidence onto reticular planes θ_B to the diffracted wavelength λ through the d-spacing d_{hkl} of reticular planes (n being the order of diffraction).

Since every ring diffracts toward the same point but has a different radius, the Bragg's angle θ_B is shifted from one ring to the next one. It produces a shift in the diffracted wavelength which is used to cover broad energy bands. However to obtain a continuous coverage each ring must diffract a bandpass large enough to overlap with the contribution of its neighbors. That is why perfect crystals are not suitable, instead mosaic crystals or crystals having curved planes are required [3, 9].

This new approach to a gamma-ray telescope has proved to be feasible and viable on several occasions. Between 2001 and 2003 a team led by CESR (France) tested the CLAIRE prototype made of 556 germanium (Ge) mosaic crystals tiles during ground tests and two balloon flights [10]. More recently a team of the Ferrara's University (Italy) managed to assemble a first lens prototype made of 20 copper (Cu) crystals, and a second one is foreseen in 2009 [11]. In parallel, detailed studies started to refine all parameters in order to design lenses exploitable for astrophysics. This led to the MAX mission concept that was studied at CNES for one year in phase 0 [12], and more recently to the GRI. Current R&D activities are divided up over three places in Europe: at CESR as well as in the University of Ferrara methods for accurate assembling of crystals are investigated, while in IASF-Roma a prospective for 'new' efficient diffracting materials is being conducted [9].

4. Transmission of polarization by a Laue lens

Since the radiation from celestial sources is diffracted in the crystal volume before hitting the detector, the question is: does the lens affect the polarization of radiation? and its consequence: does the polarization of radiation modulate the efficiency of diffraction? In the case of the symmetrical transmission geometry (the relevant case for a laue lens), the dynamical theory of diffraction gives for the reflectivity[1] integrated over the diffraction profile in a non-absorbing perfect crystal the following expression (see e.g. [14]):

$$R_{crystallite} = \frac{\pi\, d_{hkl}}{2\Lambda_0 \cos\theta_B} \int_0^{\frac{2\pi t}{\Lambda_0}} J_0(z)dz, \tag{4.1}$$

where t is the thickness of the small perfect crystal, Λ_0 is the extinction length, and J_0 the Bessel function of zero order. The extinction length is inversely proportional to the polarization factor C that expands as

$$C^2 = \cos^2\alpha \cos^2 2\theta_B + \sin^2\alpha, \tag{4.2}$$

where θ_B is the Bragg's angle and α is the angle between the polarization direction and the diffraction plane[2]. Thus depending on whether the polarization of the incident wave is in the diffraction plane (π-polarization) or perpendicular to it (σ-polarization), the polarization factor takes the form $C_\pi = \cos 2\theta_B$ or $C_\sigma = 1$.

In Darwin's model a mosaic crystal can be seen as an assembly of independent tiny perfect crystals, *the crystallites*, each slightly misaligned with respect to the others. This model is used to predict the intensity diffracted by a mosaic crystal. It is based on the dynamical theory to describe the diffraction in crystallites. The result is the following expression for the reflectivity of a macroscopic mosaic crystal of thickness T:

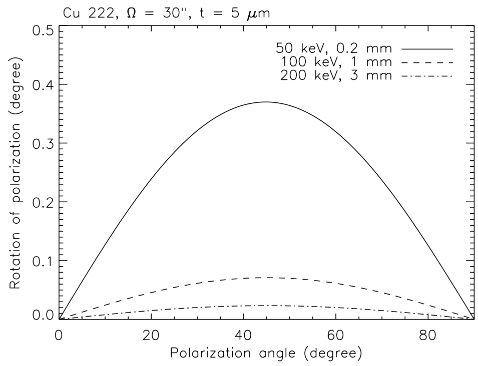
$$R_{mos} = \frac{I_h}{I_0} = \frac{1}{2}\left[1 - \exp\left(-2W(\Delta\theta)\, R_{crystallite}\,\frac{T}{t}\right)\right] \exp\left(-\frac{\mu T}{\cos\theta_B}\right), \tag{4.3}$$

$\Delta\theta$ being the angular deviation between the actual incidence angle of the beam and Bragg's angle, W the angular distribution function of crystallites (generally considered as Gaussian) and μ the linear absorption coefficient.

The angle of polarization of the diffracted beam, α_h is given by:

[1] defined as the ratio of the diffracted over the incident beam intensity

[2] the plane containing the incident and the diffracted rays, not to be mixed up with *diffracting planes*, the reticular planes on which radiations are diffracted



E (keV)	T (mm)	$R_{mos,\sigma}$	$R_{mos,\pi}$	$\frac{R_{mos,\sigma}-R_{mos,\pi}}{R_{mos,\sigma}}$
50	0.2	0.2409	0.2347	2.574 x 10^{-2}
100	1.0	0.2898	0.2883	5.176 x 10^{-3}
200	3.0	0.2551	0.2547	1.568 x 10^{-3}

Figure 2: Effect of the diffraction in a Cu crystal on the 222 reflection on radiations of 50, 100 and 200 keV. For each energy the thickness of the mosaic crystal is adapted in order to maximize the reflectivity. *Left*: Rotation of the polarization as a function of the angle between the diffraction plane and the polarization direction. *Right*: Effect on the diffracted wave amplitude.

$$\alpha_h = \arctan\left(\frac{\|\vec{E}_{h\perp}\|}{\|\vec{E}_{h/\!/}\|}\right) = \arctan\left(\sqrt{\frac{I_{h\perp}}{I_{h/\!/}}}\right) = \arctan\left(\sqrt{\frac{R_{mos,\sigma}}{R_{mos,\pi}}}\right) \tag{4.4}$$

We consider hereafter the example of a Cu crystal diffracting at the second order on planes (111) (reflection 222) at 50 keV, 100 keV and 200 keV. The rotation of the polarization $\alpha_h - \alpha$ is plotted in Figure 2. Even for 50 keV where Bragg's angle is far from negligible ($\theta_B = 6.82°$), the effect of the lens is insignificant. The modulation of diffracted intensity due to the polarization is also negligible at the energies of interest, as shown in the table of Figure 2. Thus we can state that a Laue lens does not affect the polarization of radiation on its energy range (>50 keV), and consequently that it allows the possibility to determine it at the focal plane.

The transmission of the beam polarization through diffraction in a Cu crystal has recently been investigated experimentally at the ESRF (Grenoble, France) at energies between 100 and 750 keV, confirming the fact that there is no visible effect [13].

5. Conclusion

Thanks to the efforts of the French, Italian and European Space Agencies Laue lens technology is getting more and more mature allowing hope to have a telescope ready for celestial observations on a short timescale. It has been shown that a Laue lens does not affect the polarization of radiation that it diffracts and that consequently it is possible to study the polarization of the emission from celestial objects in the focal plane of a Laue lens telescope. This opens new possibilities for this emerging field: thanks to the lens that concentrates radiation, the signal to background ratio is enhanced as compared to non-focusing mission concepts, which allow the measurement of low polarization fractions.

The requirements on the focal plane instrument are "naturally" well suited for polarization measurements, since to take full advantage of the imaging capabilities of the lens as well as to minimize the instrumental background, the focal plane has to be finely pixelated. With good timing resolution, it becomes possible to perform Compton tracking of the events. This would allow the rejection of events whose cone of possible direction of incidence does not intercept the lens and the determination of the radiation's polarization thanks to the non-uniformity in the azimuthal distribution of Compton scattering for a polarized beam.

As a result, a Laue lens telescope such as GRI, could combine in the hard X / soft gamma ray domain high sensitivity, polarimetry, timing, and this with an angular resolution of $\sim$ 0.5 - 1 arcmin in a field of view of a few arcmin: a powerful tool for high-energy astrophysics.

Acknowledgement

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