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Crystals for X/gamma-ray space telescopes

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Summary. — We will review the status of the Laue lens development of space astrophysics and the importance of the curved crystals for optimizing the lens performance.

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1. – Introduction

For a breakthrough in the study of the high-energy physical processes occurring in Galactic and extragalactic sources, it is crucial to have an instrumentation that covers a broad energy band (from fraction of keV to several hundreds of keV) and that it shows a high flux sensitivity even on short time scales (possibly on time scales shorter than source time variability). To meet both requirements it is crucial to use focusing telescopes. The current experimental scenario is the following: low-energy X-ray (0.1–10 keV) telescopes are available and are well tested in space; medium-energy X-ray (up to 70–80 keV) telescopes, based on multilayer mirrors, will be tested in space in the next future (American "NUSTAR" mission, Japanese "ASTRO–H" mission); high-energy X-ray ($> 70/100$ keV) telescopes are still under development.

But, why to extend the band up to high-energy X-rays (also called soft gamma-rays) ($> 70/100$ keV)? For a review of the science goals in this energy band, see, *e.g.*, ref. [1]. In short, some scientific reasons are the following:

– to study the spectral formation physics in the presence of strong magnetic fields;

– to study soft and very soft states of Galactic Black Hole Binaries (BHBs);

– to investigate the physical origin of high-energy cut-offs in AGNs spectra;

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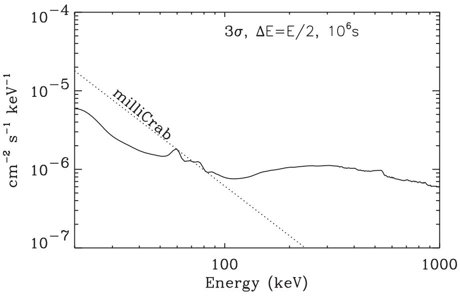

Fig. 1. – Sensitivity to continuum emission of the IBIS-ISGRI telescope aboard the INTEGRAL satellite now in flight. Reprinted from ref. [4].

– to establish the origin of the high energy ($> 60\,\mathrm{keV}$) Cosmic X-ray Diffuse Background;

– to determine the production sites the e^+/e^- annihilation line, and its origin.

As an example, we consider the last science goal. Positron production can occur in a variety of cosmic explosions and acceleration sites. It is expected to be the result of the presence of antimatter but it is also expected in the case of dark matter. Thus the observation of the characteristic 511 keV annihilation line provides a powerful tool to probe plasma composition, temperature, density and ionization degree. A claim for an annihilation line from a compact source (Nova Muscae) was reported but never confirmed [2]. Instead evidence of diffuse annihilation line emission from the Galactic Center region was found with the INTEGRAL satellite [3]. The origin of this emission is still not established, even if the authors of the paper [3] suggest as possible origin the hard X-ray compact sources located in the region. The test of this assumption and thus establishing the sources of the 511 keV line in compact sources requires much more sensitivity, achievable only with focusing gamma-ray telescopes.

The requirements for future hard X/γ-ray focusing telescopes can be summarized as follows:

– broad band (80/100–600 keV and beyond);

– continuum sensitivity 2 orders of magnitude better than current non-focusing telescopes (design goal: 10^{-8} ph/(cm^2 s keV) in an observation time $T = 10^5$ s);

– good imaging capability (angular resolution ≤ 1 arcmin).

As an example of limit sensitivity of the current instrumentation, we show in fig. 1 the continuum sensitivity of the ISGRI instrument aboard the INTEGRAL satellite.

2. – Laue lens principles

We propose as focusing instrument in the soft gamma-ray band a Laue lens. Laue lenses use the interference between the periodic nature of the electromagnetic radiation and a periodic structure such as the matter in a crystal. In a Laue lens, the photons pass through the full crystal, using its entire volume for interacting coherently. In order

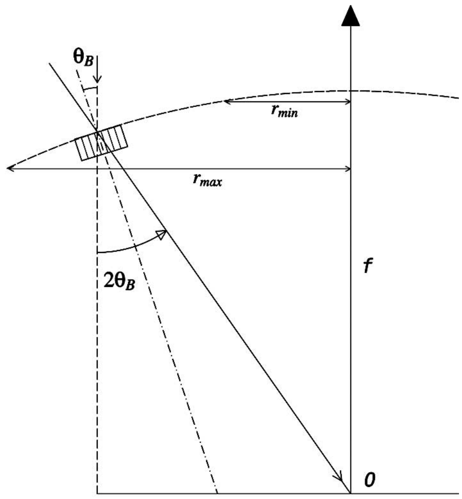

Fig. 2. – Geometry of a Laue lens (see text).

to be diffracted, an incoming gamma-ray must satisfy the Bragg condition:

$$2d_{hkl} \sin\theta_B = n\frac{hc}{E}\,, \tag{1}$$

where d_{hkl} (in Å) is the spacing of the lattice planes (hkl), n is the diffraction order, $hc = 12.4\,\text{keV·Å}$ and E is the energy (in keV) of the gamma-ray photon.

A Laue lens for astrophysical applications is made of a large number of crystals, in transmission configuration (Laue geometry), that are disposed such that they will concentrate the incident radiation onto a common focal spot. A convenient way to visualize the geometry of a crystal lens is to consider it as a spherical cup covered with crystal tiles having their diffracting planes perpendicular to the sphere (see fig. 2). The focal spot is on the symmetry axis at a distance $f = R/2$ from the cup, with R being the radius of the sphere of which the spherical cup is a part; f is called the *focal length*. The main requirement for the disposition of the crystals in the lens is to get a smooth dependence of the lens effective on photon energy. Two are the possible dispositions: ring-like for high focal lengths ($> 20\,\text{m}$) and spiral-like for lower focal lengths (see fig. 3).

3. – Ongoing developments and main issues

The development of Laue lenses is mainly performed in Europe within two institutes: CESR (Centre d'Etude Spatiale des Rayonnements) in Toulouse (France) and the Physics Department of the University of Ferrara, in Italy. In the former insitution, the main goal is the development of narrow-band (800–900 keV) Laue lenses for nuclear astrophysics, while in the latter institution the goal is the development of broad-band Laue lenses (70/100–600 keV).

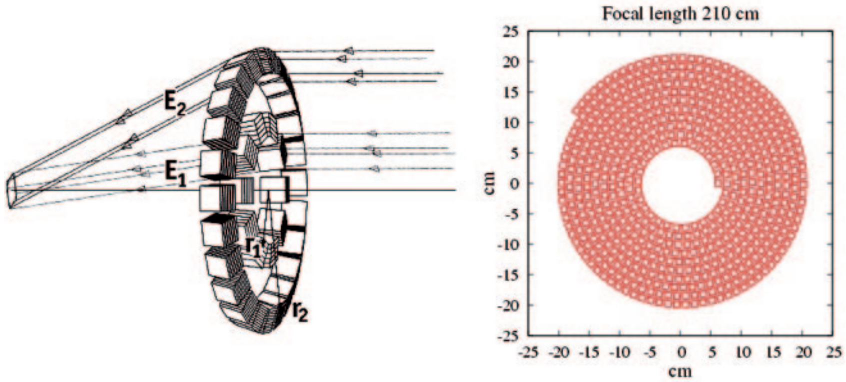

Fig. 3. – The basic design of a crystal diffraction lens in Laue geometry. Flat crystal tiles are assumed. Left: concentric rings of a given radius r concentrating a constant energy E. Right: crystal tiles disposed along an Archimedes' spiral result in a continuously varying energy E. Given the footprint of the crystals, the image in the focal plane has a minimum size equal to that of the crystal size.

The main issues to be faced for the Laue lens development are two:

a) development of a proper technology for the massive production of suitable crystals;

b) development of a technology for assembling thousands of crystals in a reasonable time, compatible with a space project.

4. – Crystals for Laue lenses

Both mosaic crystals and curved crystals are suitable to be used for a Laue lens. See ref. [1] for an exhaustive review.

4˙1. *Mosaic crystals*. – Mosaic crystals are made of misaligned perfect microcrystals, with misalignment distribution well described by a Gaussian function:

$$W(\Delta) = \frac{1}{\sqrt{2\pi}\eta} \exp\left[-\frac{\Delta^2}{2\eta^2}\right], \tag{2}$$

where Δ is the magnitude of the angular deviation from the mean, while $\beta_m = 2.35\eta$ is the FWHM of the mosaic spread and it is called *crystal mosaicity*.

The energy passband of a mosaic crystal is given by

$$\Delta E = \frac{2d_{hkl} \cdot E^2 \cdot \beta_m}{nhc}, \tag{3}$$

where E is the energy derived from eq. (1). In fig. 4 we clarify the concept of mosaic structure.

Mosaic crystals of Copper are currently produced by ILL, while mosaic crystals of germanium are developed by IKZ, Berlin. Instead mosaic crystals of GaAs are being developed by CNR, IMEM, Parma, Italy. Also available are commercial crystals, produced

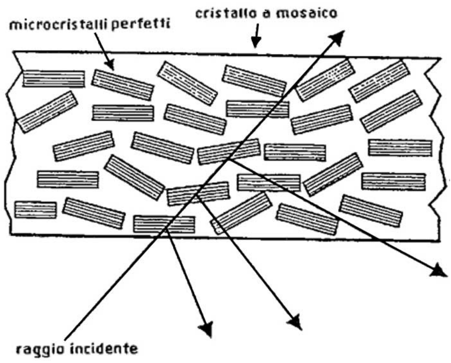

Fig. 4. – Mosaic structure concept.

by, *e.g.*, Mateck Gmbh. In fig. 5, top panel, we show the expected peak reflectivity of mosaic crystals made of different materials, for optimized values of the crystallite thickness and mosaic crystal thickness. Instead in fig. 5, right panel, we show the measured diffraction efficiency (ratio between diffracted and transmitted beams) at 300 keV.

4·2. *Curved crystals*. – Curved cystals have important advantages with respect to mosaic cystals:

- No limit to their diffraction efficiency, while for mosaic crystals the maximum theoretical value of the diffraction efficiency is 0.5.
- Better lens focusing for a proper crystal curvature.
  The better lens focusing is shown in fig. 6. It is found that for the same focal length, the angular resolution of a lens made of curved crystals significantly improves. As an example, for 20 m focal length, the angular resolution increases from 3.5 arcmin to 20 arcsec, with the source image area that decreases by a factor about 100. As a consequence of only this area decrease, the lens sensitivity increases by a factor at least 10 with respect to flat mosaic crystals. As an example, in fig. 7 we compare the sensitivity of a 20 m focal length Laue lens made of curved mosaic crystals with that made of flat mosaic crystals tiles of size $15 \times 15\,\text{mm}^2$ and 30 arcsec mosaicity.

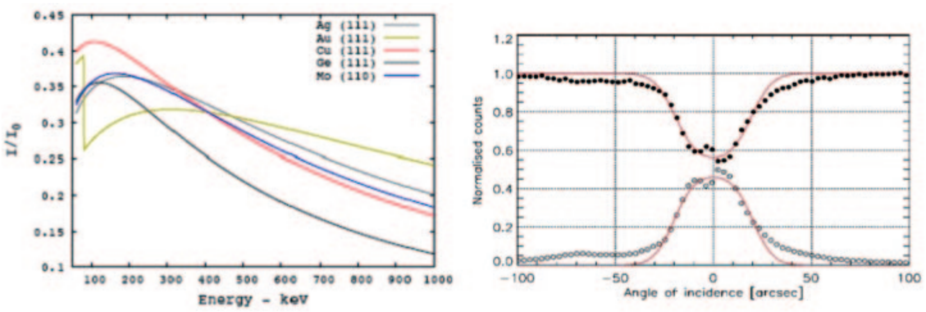

Fig. 5. – Left panel: expected maximum reflection efficiency of mosaic crystals of different materials (reprinted from ref. [1]. Right panel: Measured diffraction efficiency of a Cu(111) mosaic crystal sample at 300 keV. Reprinted from ref. [5].

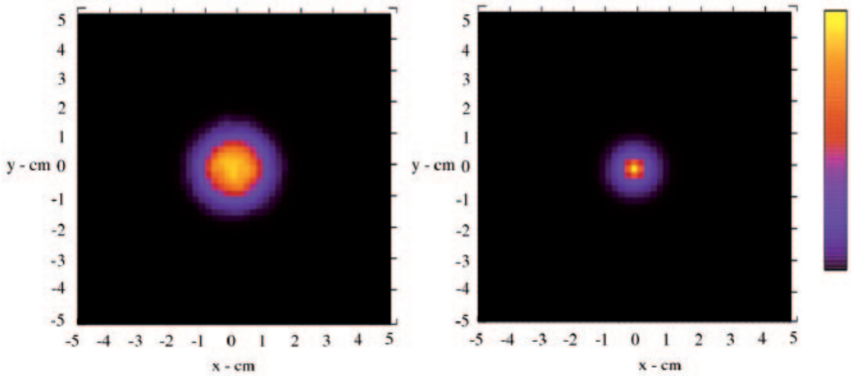

Fig. 6. – On axis response function (PSF) of a lens of 15 m focal length made of mosaic crystals of Cu(111) with 30 arcsec mosaicity, for an on-axis source. Left panel: Flat crystals with cross-section of $15 \times 15\,\text{mm}^2$. Right panel: Curved crystals with a curvature radius of 30 m.

There are several production methods to get curved crystals, among which the growing of a two-component crystal whose composition varies along the crystal growth axis (see, *e.g.*, ref. [6]), and the indentation of one face of a wafer. The last technique is being developed at the University of Ferrara with very satisfactory results for silicon and germanium (see fig. 8). Also the deposition of a coating on a wafer is being tested at the same University.

In spite of these exciting results, further efforts are needed: a) to extend the bending techniques to other crystal materials, even mosaic crystals; b) to bend thicker crystals; c) massive production (thousands of pieces) of properly curved crystal tiles as requested by space lenses.

5. – Lens assembly technology development

Currently new lens assembly technologies are being developed at the University of Ferrara, for building broad passband (70/100–600 keV) Laue lenses, and at CESR, for building high-energy narrow-passband (800–900 keV) Laue lenses. Results of these developments are reviewed in ref. [1].

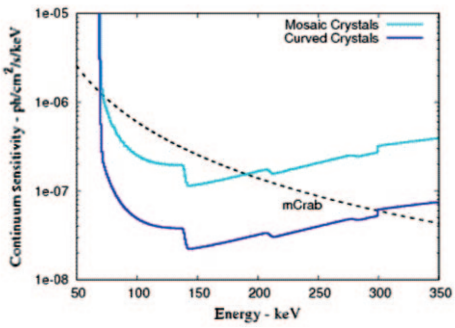

Fig. 7. – 3σ Sensitivity of a 20 m focal length Laue lens made of flat mosaic crystal tiles of Cu(111) with 30 arcsec mosaicity and 70–300 keV nominal energy passband, compared with the corresponding lens in the case that the crystals are properly curved. The time measurement assumed is 10^5 s, while the energy bins have an amplitude $\Delta E = E/2$.

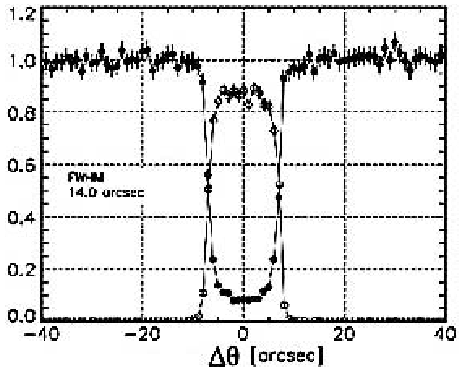

Fig. 8. – Measured rocking curve, in transmission geometry at 150 keV, of a Si(111) crystal curved at the University of Ferrara. $\Delta\theta$ gives the difference between the incidence angle of the monochromatic photon beam and the Bragg angle. Open circles: ratio between measured intensity of the diffracted beam and measured intensity of the transmitted beam (also called *diffraction efficiency*). Filled circles: difference between transmitted and diffracted intensities. Note that the angle $\Delta\theta$, through the Bragg law, is related to the reflected photon energy. Thus the figure also shows the energy bandwidth of the curved crystal. Reprinted from ref. [7], where the crystal sample was tested.

The crystal tile positioning accuracy in the lens is the most critical issue. It depends on the mosaic spread and the focal length. Longer focal lengths require better positioning accuracies, thus the development is more challenging for lenses working at the highest energies.

5˙1. *Activity at the University of Ferrara.* – In Ferrara, the developed crystal assembling technology is found suitable for building lenses with moderately short ($\leq 10-15$ m) focal lengths. It does not require any mechanism for a fine adjustment of the crystal orientation once the crystal is positioned in the lens frame. Using this technology, a first lens prototype with 6 m focal length has already been developed and tested. It makes use of mosaic crystals of Cu(111). The difference between the measured response function of the first prototype and that expected in the case of a perfect mounting of the crystals in the lens is shown in fig. 9. As can be seen, only the center part of the measured image (*i.e.*, the black region) is subtracted by the expected image. The corona still visible in the difference image is the result of the cumulative error (mainly that due to the mechanical separation of the lens from the countermask) done during the lens assembly process. A new prototype is being developed that takes into account the experience gained constructing the first one [8].

For long focal length lenses (up to 100 m), new crystal assembly technologies are required. To this end, a new project, "LAUE", supported by Italian space agency ASI, has been started with the contribution of the Italian industry (main contractor DTM, Modena). The main goals of the LAUE project are the following:

– To develop a technology for building petals of long-focal-length lenses;

– to assemble and test a lens petal (see fig. 10) with 20 m focal length;

– to develop a technology for a massive production of proper crystals;

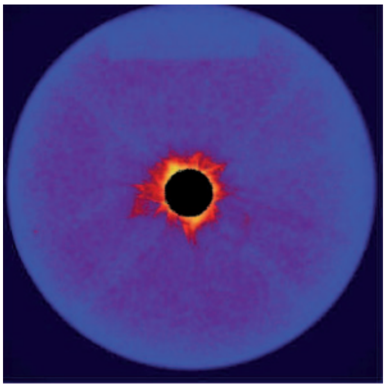

Fig. 9. – Difference between the PSF measured and that obtained with a Monte Carlo code by assuming a perfect positioning of the crystal tiles in the lens. Reprinted from ref. [9].

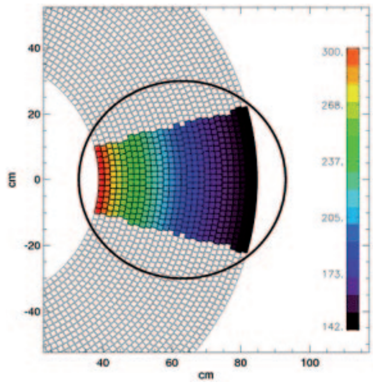

Fig. 10. – Sketch of the lens petal planned to be developed within the LAUE project.

– to produce the crystals needed to assemble the lens petal above;

– to perform a feasibility study of a space lens.

Participants to the LAUE project include, in addition to DTM and the High-Energy Astrophysics group of the University of Ferrara (UNIFE), the Sensor and Semiconductor Laboratory of UNIFE, the CNR Institute IMEM (Istituto dei Materiali per l' Elettronica ed il Magnetismo) Parma; the Institute INAF–IASF (Istituto di Astrofisica Spaziale e Fisica cosmica) Bologna; branches of Milan and Turin of the Thales-Alenia Space industry in Italy.

6. – Conclusions

The hard X/γ-ray band covered by Laue lenses is crucial for high-energy astrophysics. Given their much higher expected sensitivity (two orders of magnitude better than the current instrumentation), Laue lenses can face key importance astrophysical issues. Curved Diffracting Crystals (CDC) appear the best crystals for Laue lenses. Technologies already developed (*e.g.*, indentation) to produce CDC are very promising. A technology developed for assembling Laue lenses with low focal length(up to 10–15 meters) are already tested, with further results expected in a few months. A technology for building high-focal-length Laue lenses is under development (LAUE project) with the industry involvement.

* * *

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