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MAX: Development of a Laue diffraction lens for nuclear astrophysics

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Abstract

The next generation of instrumentation for nuclear astrophysics will have to achieve an improvement in sensitivity by a factor of 10–100 over present technologies. With the focusing gamma-ray telescope MAX we take up this challenge and propose to combine the required sensitivity with high spectral and angular resolution, and the capability to measure the polarization of the photons. MAX is a space-borne crystal diffraction telescope, featuring a broad-band Laue lens optimized for the observation of compact sources in two wide energy bands of high astrophysical relevance. Gamma rays will be focused from the large collecting area of a crystal diffraction lens onto a very small detector volume. As a consequence, the signal to background ratio is greatly enhanced, leading to unprecedented sensitivities.

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1. Introduction

Since its launch in 2002, the INTErnational Gamma RAy Laboratory (INTEGRAL) observatory is providing a global overview of the soft gamma ray. New and exciting gamma-ray sources are being detected, and now there is a growing interest in the capability of performing deeper, more focused investigations. To improve our understanding of the most violent phenomena of the Universe, the next generation of instruments will have to achieve a gain in sensitivity of 10–100 over present technologies.

To reach this goal, the concept of a gamma-ray telescope featuring a crystal diffraction lens is proposed. Compared to existing instruments relying on inelastic interaction processes—geometric optics (shadowcasting in modulating aperture systems) or quantum optics (kinetics of Compton scattering)—focusing allows to decouple the collecting area from the sensitive area. Since in space the background count rate in a gamma-ray detector is roughly proportional to its volume, focusing from a large collecting area onto a small detector leads to high signal to noise ratios, and so to high sensitivities.

MAX lens is based on Bragg diffraction in the volume of crystalline materials. A prototype of such a Laue lens, called CLAIRE, has already been realized in a collaboration

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CESR—CNES (the Franch space Agency), it has demonstrated the feasibility of this concept [1].

In this paper, a brief review of the principle of a Laue lens is given, followed by a description of the MAX mission. We also present a brief history of the R&T program CLAIRE, and describe ongoing MAX R&D for the development of a space borne Laue lens.

2. The principle of Laue lenses

In a crystal diffraction lens, crystal tiles are positioned such that they diffract the incident radiation of a certain energy onto a common focal spot according to the Bragg relation $2d_{hkl}\sin(\theta_B) = n\lambda$ as illustrated in Fig. 1. This formula links a wavelength λ to the Bragg angle θ_B (diffraction angle) for a particular set of crystalline planes $[h\,k\,l]$ in the crystal and for a given diffraction order n.

Crystals suitable for a Laue lens must have a non-zero angular acceptance, i.e. a given wavelength must be diffracted for a non-zero range of incident angles. Such crystals are called mosaic crystals because they are well described by a juxtaposition of independent, and slightly differently oriented, small single crystals—the crystallites—as in a mosaic. The mosaic spread of a crystal is described by the mosaicity, which is given by the FWHM of the distribution function of the crystallite orientations.

A crystal angular acceptance $\Delta\theta$ is related to its energy bandpass $\Delta\lambda$ through the relation $\Delta\lambda/\lambda \approx \Delta\theta/\theta$ derived from the Bragg relation. A mosaic crystal thus diffracts an energy bandpass ΔE centred on a value which depends to the crystal's radial position on the lens (since the focal length F_∞ is fixed, the radius r imposes the diffraction angle): $\Delta E \approx (2F_\infty/r)E\Delta\theta$.

Two subclasses of crystal diffraction lenses can be identified—narrow bandpass Laue lenses and broad bandpass Laue lenses. Narrow bandpass Laue lenses use a different set of crystalline planes $[h\,k\,l]$ for every ring in order to diffract photons in only one energy band centred on an energy $E1 = E2$ (Fig. 1). Broad bandpass Laue lenses use one or very few sets of crystalline planes—typically the lowest order planes [1 1 1] or [2 0 0] whose diffraction efficiency is optimum. Since several adjacent rings use the same set of planes, each focuses a slightly different energy because of the varying radii. This type of lens can cover a broad energy band. However, if a large geometric area is required, Laue lenses involve very long focal lengths because of the small Bragg angles values.

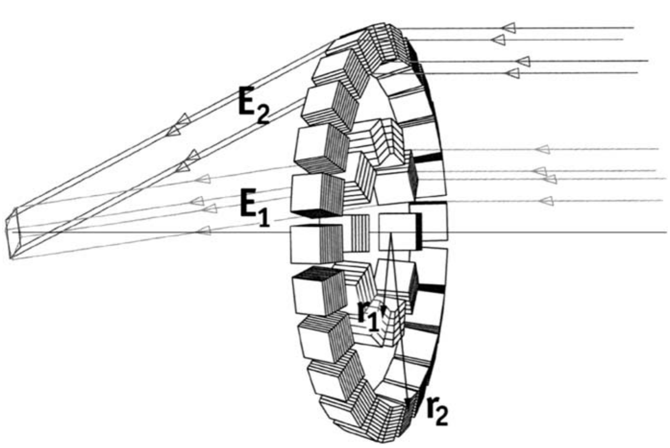

Fig. 1. The basic design of a crystal diffraction lens.

3. The MAX mission

3.1. Lens features and mission objectives

The MAX mission is a space borne gamma-ray telescope consisting of two satellites flying in formation in order to achieve 86 m of focal length between the Laue lens and the detection plane. In the current design, the lens is made of 7870 copper and germanium crystal tiles of 1.5 cm × 1.5 cm, distributed on 24 concentric rings with radii ranging from 56 to 80 cm and from 96 to 112 cm (Fig. 3). The mosaicity of the crystals is 30 arcsec, their total weight is about 120 kg.

The resulting lens focuses simultaneously in two broad energy bands corresponding to the scientific objectives of the mission, i.e. the study of Type Ia supernovae (SN) and compact objects. The bandpasses of 10 Cu rings and 3 Ge rings superimpose to cover an energy band from 800 to 900 keV, with the aim to observe the 847 and 812 keV nuclear lines emitted by SN Ia. The effective area is 500 cm^2 at 847 keV. A sensitivity of $\sim 10^{-6}$ cm^{-2} s^{-1} to broadened gamma-ray lines allows to expect ~5 observations of SN Ia per year, within distances up to 50 Mpc [2].

The second energy band is centred on 500 keV in order to observe the electron—positron annihilation line at 511 keV. A significant numbers of positrons is expected to be released from compact objects, both galactic and extragalactic, such as microquasars, X-ray binaries, active galactic nuclei, solar flares and the high energy afterglow from gamma-ray bursts. Here the bandpasses of 9 Cu rings and 2 Ge rings combine to cover an energy band from 450 to 540 keV, with a cumulated effective area of 725 cm^2 at 511 keV. In this bandpass, the 478 keV decay line from ^{7}Li in classical novae constitutes another important objective.

3.2. Detector features

The baseline detector for MAX is a stack of planar Ge detectors using orthogonal strips, cooled by a passive radiator and actively shielded by BGO scintillators. Alternative solutions include (i) a single high purity germanium detector, (ii) an efficiency optimized narrow field of view Compton camera featuring Si strips and CdTe pixels [3,4], and (iii) an array of low temperature calorimeters (detection of phonons produced by the impinging photons [5]).

The advantages of using a detector providing localization of the interactions are multiple: besides following the excursions of the focal spot across the detector plane, such