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Opening the path to hard X-/soft gamma-ray focussing: The ASTENA-pathfinder mission

E. Virgilli(1), L. Amati(1), N. Auricchio(1), E. Caroli(1), F. Fuschino(1),
M. Orlandini(1), J. Stephen(1), L. Ferro(2), F. Frontera(2),
M. Moita(2), P. Rosati(2), M. Caselle(3) and C. Ferrari(4)(5)

(1) *INAF/OAS - Bologna, Italy*
(2) *Dipartimento di Fisica e Scienze della Terra, Università di Ferrara - Ferrara, Italy*
(3) *Karlsruher Institut für Technologie - Karlsruhe, Germany*
(4) *CNR/IMEM - Parma, Italy*
(5) *INAF/OAB - Brera, Italy*

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Summary. — Hard X-/soft gamma-ray astronomy is a crucial field for transient, nuclear and multimessenger astrophysics. However, the spatial localization, imaging capabilities and sensitivity of the measurements are strongly limited for the energy range $>$70 keV. To overcome these limitations, we have proposed a mission concept, ASTENA, submitted to ESA for its program "Voyage 2050". We will report on a pathfinder of ASTENA, that we intend to propose to ASI as an Italian mission with international participation. It will be based on one of the two instruments aboard ASTENA: a Laue lens with 20 m focal length, able to focus hard X-rays in the 50–700 keV passband into a 3-d position sensitive focal plane spectrometer. The combination of the focussing properties of the lens and of the localization properties of the detector will provide unparalleled imaging and spectroscopic capabilities, thus enabling studies of phenomena such as gamma-ray bursts afterglows, supernova explosions, positron annihilation lines and many more.

1. – Rationale and mission configuration

High energy astrophysics has still unanswered questions mainly due to the poor sensitivity of the present instrumentation: transient events like gamma-ray bursts and in particular their X-ray afterglow emission, blazar and magnetar spectra are just a few examples of science that would benefit from higher-sensitivity instruments. An exhaustive review of the science that can be tackled with future focusing optics can be found in [1]. A substantial increase in sensitivity can be achieved by enabling hard x-ray focusing through Laue lenses which are based on diffractive crystals (fig. 1, left). At present, new technologies for the production of effective optics and new materials for gamma-ray detection make Laue's lenses mature for their adoption in space. A hard x-ray mission concept named ASTENA (Advanced Surveyor of Transient Events and Nuclear Astrophysics) [2] has been proposed for focusing photons in the 50–700 keV energy range. The ASTENA mission consists of two complementary instruments: a Wide Field Monitor

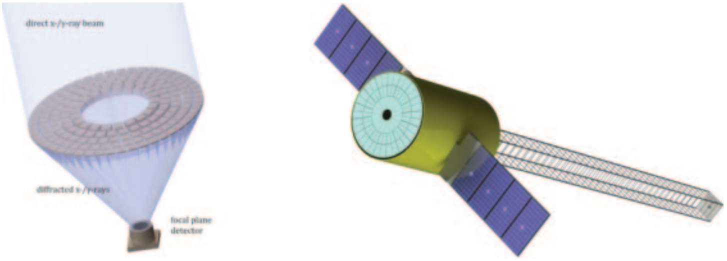

Fig. 1. – Left: drawing of the Laue lens concept. Right: drawing of the ASTENA pathfinder. The blue circular area represents the Laue lens, which is divided into independent modules. A position-sensitive detector is positioned at the focal distance of 20 m through an extendable mast.

with Imaging and Spectroscopic capabilities (WFM-IS), based on the same technology of the THESEUS/XGIS instrument [3] and a Narrow Field Telescope (NFT) [4]. The NFT is based on a Laue lens made from bent crystals of silicon and germanium. The Laue lens has a diameter of 3 m and a focal length (FL) of 20 m. Due to the single reflection/diffraction principle, the NFT has a narrow field of view of about 4 arcmin, above this limit the source in focus broadens due to aberrations. As a precursor for the ASTENA mission, we propose an experiment based on NFT alone, whose total weight would be suitable for the size of a possible light national mission, in response to the next upcoming ASI call. This configuration, called ASTENA-pathfinder (fig. 1, right), will allow us to tackle a relevant scientific case with a low mission weight (<200 kg). In the following Sections we describe the status of the relevant technologies involved in the development of this ambitious mission proposal.

2. – Development activities for Laue lenses

Laue lens realization is a complex task that is mainly limited by the large number of basic optical elements to be prepared and accurately oriented towards a common focal point. Since the alignment process has been done manually so far, it is time-consuming and prone to inaccuracies. Several projects have been proposed in order to increase the technological maturity of the Laue lenses. Within the recent TRILL project [5], funded by ASI-INAF, we have investigated different aspects of the process: 1) optimizing the preparation of crystals with the nominal curvature radius of 40 m (twice the FL) and 2) develop and automate the alignment to reduce uncertainties and processing times. Concerning point 1, CNR/IMEM (Parma) has optimised a repeatable method based on lapping one of the largest surfaces to impress the nominal curvature radius. With reference to point 2, at Karlsruher Institut für Technologie (KIT) the use of the flip chip bonding technology has been evaluated. This method allows setting several crystals per minute at the same Bragg angle. However, the alignment angle depends critically from the miscut angle with respect to the external surface, therefore the alignment procedure relies also on the miscut reduction of the sample. These methods achieve, in a single step, the accurate bonding of crystals to a common substrate and their bending to the nominal radius of curvature. A method for the crystal's alignment which is now under investigation involves the use of elastically adjustable supports (called lamellae) operated by micro screws (fig. 2, right). Each crystal is bonded through adhesive on the top of a lamella and fine threads micro screws ensure alignment accuracy of the order of a few arcsec. A prototype with 9 crystals has been designed and will be realized and tested

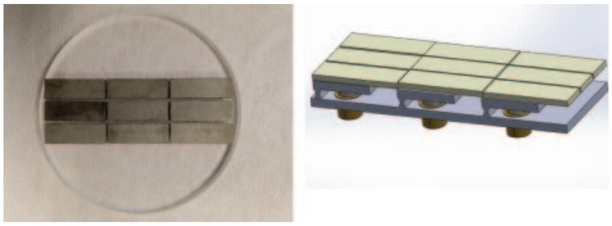

Fig. 2. – Left: module of Laue lenses realized at Karlsruher Institut für Technologie (KIT) made with 9 bent Germanium crystals bonded on a 4 mm quartz substrate. Right: drawing of a 9-element prototype which exploits an adjustable lamella.

soon. Through the irradiation of the prototype we will evaluate the capability to orient the crystals at their correct angle in order to focus the radiation at the common point.

3. – Activities for the development of the focal plane detector

Technology activities for the development of solid-state detectors for spectroscopy, imaging, and polarimetry for astrophysical purposes are being carried out by several research groups in Europe [6,7]. One of the goals of these R&D activities is the realization of a focal plane detector suitable for coupling with a Laue lens. The main requirements for such a focal plane detector are: 1) high detection efficiency ($>80\%@500\,\mathrm{keV}$), 2) high performance spectroscopy ($\leq 1\%$ FWHM @ 511 keV) and 3) imaging capability with sub-millimeter spatial resolution in the three dimensions ($\leq 300\,\mu\mathrm{m}$) and fine timing resolution. In this perspective, Cadmium Zinc Telluride (CZT) has very high detection efficiency in the sub-MeV range even with a few cm of materials and good spectroscopic capability of about 1% FWHM @ 511 keV. It is particularly interesting also for the advantage of being usable at room temperature. Since the Laue lens PSF is of the order of 30 arcsec (HPD), at 20 m focal length the resolution of the detector must be of the order of 0.3–0.5 mm to allow the PSF to be mapped with a sufficient number of spatial bins (5–10 pixels). The baseline technology that will be adopted for the NFT detector is that of CZT Drift Strip detectors which employs a number of drift strips, and anodes and cathodes readout strips placed on the two opposite sides of the CZT crystal. The segmentation of both anodes and cathodes (which are perpendicularly arranged with respect to each other) allows for a highly segmented sensor providing thousands of virtual sub-millimetric voxels with only a few tens of read-out channels (fig. 3) and, most importantly, sensitive in the three directions, where the depth coordinate is determined by the ratio between the anodic and cathodic signals. This feature allows Compton reconstruction of the events which also enables gamma-ray polarimetry. In order to reach the required thickness, a stack of crystals is necessary. The detector front-end electronics is based on custom-designed low noise charge sensitive preamplifier. The CZT sensor induces the charge pulses on the electrodes, then they are read by a multichannel Digital Pulse Processing system based on FPGA through its readout front-end. With this electronics, a time resolution of about $1\,\mu$s is achievable [8].

4. – Conclusions

We have presented an experiment called ASTENA-pathfinder based on a lightweight Laue lens coupled with a solid state focal plane detector. Thanks to the sensitivity achievable for both continuum and nuclear line observations, the ASTENA-pathfinder will

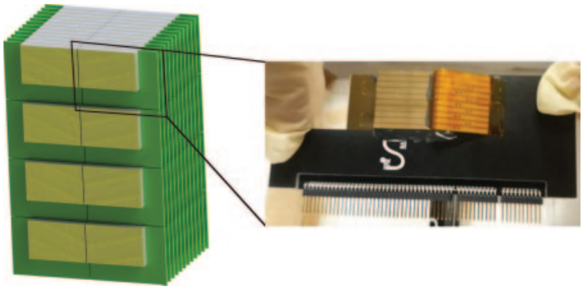

Fig. 3. – Left: the configuration of a possible focal plane detector based on a stack of CZT crystals. Right: detail of one CZT detector developed within the 3DCaTM project, supported by ASI-INAF.

represent a turning point for a number of still unanswered scientific questions. Current technological activities, also supported by ASI and INAF, address both the complexity of building a Laue optics, that requires great precision for the alignment of thousands of basic components, and the realisation of a focal plane detector with fine 3-d segmentation, fast timing capabilities, high detection efficiency, and high energy resolution.

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