ECLAIRs, A CODED MASK APERTURE TELESCOPE ONBOARD THE SVOM SPACE MISSION

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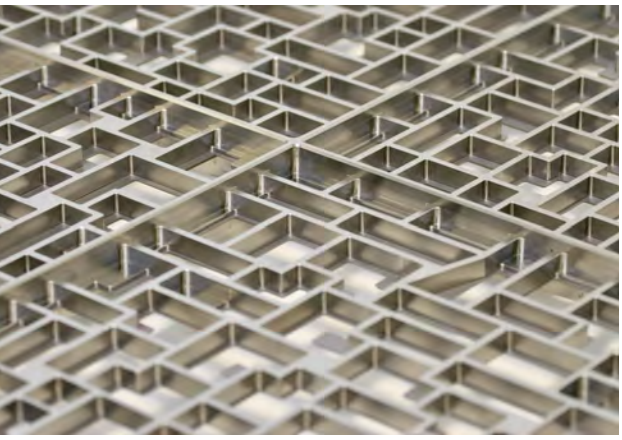

We introduce the coded mask imaging technique with a focus on the ECLAIRs instrument onboard the SVOM space mission. Detecting unknown astrophysical transient sources in the hard X-ray band requires monitoring a large part of the sky. Coded mask instruments are well suited to perform these observations. ECLAIRs, thanks to its low energy threshold, will open a new window on the transient universe but it comes with its own challenges, in particular in the design of its coded mask.

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On June 24, 2024, the SVOM (Space-based astronomical Variable Objects Monitor) space mission will be launched, concluding a collaborative effort between China and France aimed at studying high-energy astrophysical transient phenomena [1]. These phenomena, characterised by their short duration (ranging from seconds to weeks or years) compared to cosmic timescales and their significant energy releases, are typically associated with compact objects like black holes and neutron stars. They reflect profound physical changes within the astrophysical sources, sometimes resulting in the partial or complete destruction of the progenitor object. Observing transient phenomena, often done at various wavelengths, helps deepen our understanding of astrophysical mechanisms such as the accretion of matter in the vicinity of compact objects, particle acceleration to relativistic velocities, and the behavior of ultra-dense matter.

The SVOM payload comprises four instruments: a Visible Telescope (VT), a soft X-ray (0.2-10 keV) telescope (MXT), a Gamma-Ray Monitor (GRM) with scintillation counters operating between 15 keV and 5 MeV, and a hard X-ray/soft gamma-ray (4-150 keV) wide-field telescope, ECLAIRs (see Fig.1). SVOM's primary goal will be the detection of gamma-ray bursts (GRBs) linked to the final stages of the life of certain massive stars (insert 1). Investigating GRBs requires compliance with specific observational constraints. Initial detection of the gamma-ray flare is imperative, given its brief duration. Detecting and localising these GRBs will be the main task of the ECLAIRs telescope, over a wide field-of-view (FoV) covering 89×89 square degrees.

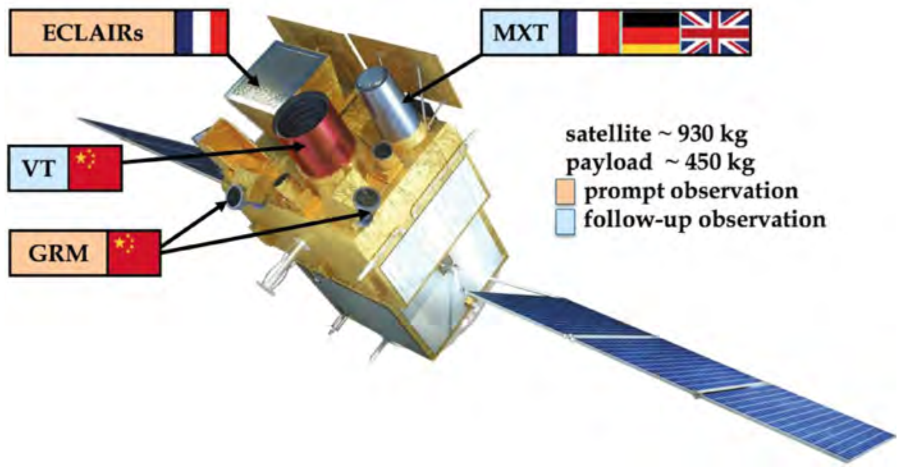

Figure 1. The SVOM satellite, with its four scientific instruments (flags indicate the countries involved in their construction). Taken with permission from CNES.

CODED MASK APERTURE TELESCOPES

Telescopes in the hard X-ray/soft gamma-ray (between ~10 keV and 10 MeV) like ECLAIRs are special since mirrors, which are ubiquitous at other wavelengths, are difficult to use in this energy range. First, as the grazing incident angle, used in X-ray mirrors, is inversely proportional to photon energy, the focal length, which is of the order of 10 m at 20 keV, would be of the order of hundreds of meters at 1 MeV. On the other hand, in the hard X-ray/soft gamma-ray domain, the radiation wavelengths become comparable to or shorter than the typical interatomic distances which then lead to absorption of the photons mainly through the photoelectric process.

Thus, at such energies, coded mask instruments (CMI) are generally used. They are multiplexing optical devices that allow reconstructing the flux and position of astrophysical sources in the FoV through the spatial modulation of the incident light depending on the source direction on the sky. CMIs follow the principle of the well-known sténopé or *camera obscura*: a hole in a mask is used to form an image on a screen. In such a system, the image of a point source is a single spot of the projected size of the hole. However, while the sensitivity increases with the aperture, the angular resolution is inversely proportional to the hole size. Hence, a practical alternative is to design a mask with several small transparent elements of the same size which modulate the signal arriving on a position sensitive detector located behind it (Fig. 3). The small size of the holes guarantees good resolution, while their large number ensures good sensitivity [4].

Assuming a detector with infinite spatial resolution and an infinitely thin mask composed of totally opaque closed elements and totally transparent open ones, the angular resolution of a coded-mask telescope is directly related to the size m of the mask elements and the mask-detector distance H by: $\theta = \arctan(m/H)$. The sensitive area instead depends on the number of transparent elements of the mask that are visible to the detector. Therefore, by either decreasing the size of the holes or increasing the distance between the mask and the detector while simultaneously increasing the number of holes, one can improve the angular resolution without sacrificing sensitivity. In addition, sensitivity is not uniform across the entire FoV, but is directly related to the fraction of the detector illuminated by a mask pattern (even if incomplete) for a given source. To characterise the FoV of a coded-mask telescope, two cases can thus be distinguished: the fully coded FoV for which the mask shadow fully covers the detector, and the partially coded FoV for which only a fraction of the detector is modulated by the mask (see Fig. 3).

With such a coded mask instrument, the detector image (also known as a shadowgram) is then a linear superposition of the shadows of the mask projected by the different sources in the FoV. The sky image is then reconstructed by applying a deconvolution procedure to the detector image based on the knowledge of the mask pattern (insert 2).

Coded masks were designed in the 1970's-1980's and have been successfully used since then in the field of high-energy astronomy. Initially deployed on balloon-borne instruments, they were later integrated into several space missions. Such a coded mask will also equip the ECLAIRs telescope onboard the forthcoming SVOM space mission. Its design is described in the following section.

THE ECLAIRs INSTRUMENT AND ITS UNIQUE CODED MASK

The ECLAIRs instrument is composed of four subparts: a coded mask, a 1024-cm^2 detection plane and its front end electronics, a passive lead shield and a processing unit. The detection plane consists of 6400 pixels made of CdTe measuring 4×4×1 mm^3 each. The processing unit allows for the control of the telescope and runs a scientific software in charge of detecting new astrophysical transient events in real time. Upon detecting a new cosmic source, the information is relayed to the platform to initiate a slew, aligning the VT and MXT instruments with the direction of the ECLAIRs trigger in order to catch the GRB afterglow emission. Simultaneously, the platform transmits its data to the ground via a dedicated VHF network distributed around the Earth, which then forwards it to the Mission Center.

The operating principle of the ECLAIRs telescope is a matter of balance: it must detect bursts with maximum sensitivity, necessitating a large sensitive area, while also determining their locations with good accuracy across a wide FoV. These constraints heavily influenced the design of the ECLAIRs coded mask, as elaborated below.

The mechanical design of the mask is driven by the mechanical resistance to the important level of vibrations that the mask has to support at launch. To complicate further the design, the mask has to be self supporting; unlike conventional masks that utilise a supporting structure for the mask elements, such an approach would inadvertently impede photon absorption within the energy range of 4 keV to 15 keV. On the other hand, to indeed absorb photons between 4 keV to 150 keV, the opaque elements of the mask are made from a

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GAMMA-RAY BURSTS

GRBs are among the most energetic cosmic explosions emitting luminosities 10^{44} J/s. They consist of two main phases: the non-thermal prompt emission, observed between 10 keV and 10 MeV and lasting between ~100 ms and ~1000 s, and the afterglow, most often detected from X-rays to radio and fading over a few months. Two classes of GRBs are identified: short GRBs with durations typically <2 s and long GRBs with durations up to hundreds of seconds. While long GRBs are associated with the death of massive stars, the detection of a gravitational-wave signal associated with a short GRB in 2017 [2], confirms that the latters are associated with the coalescence of two neutron stars. A well-accepted model for GRBs suggests that they are produced within an ultra-relativistic jet created after cataclysmic events like the formation of a black hole or a highly magnetised neutron star (see *e.g.* [3] and references therein). This scenario, described in Fig. 2, involves internal dissipation mechanisms within the jet which produces the gamma-ray prompt emission. In the final stage, the propagation of the relativistic jet in the interstellar medium creates a shock wave, leading to the deceleration of the jet. A fraction of the ejecta energy is converted into the amplification of magnetic fields and acceleration of electrons which re-emit part of this energy through synchrotron radiation, creating the long-lived afterglow. While these models provide a fundamental understanding of basic GRB properties, various complex features such as electromagnetic flares pose significant challenges for comprehensive explanation. This suggests that there are still substantial aspects of GRBs that require further understanding. Moreover, high-redshift GRBs are ideal probes of the epoch of the very first stars and galaxies, a few hundred million years after the Big Bang.

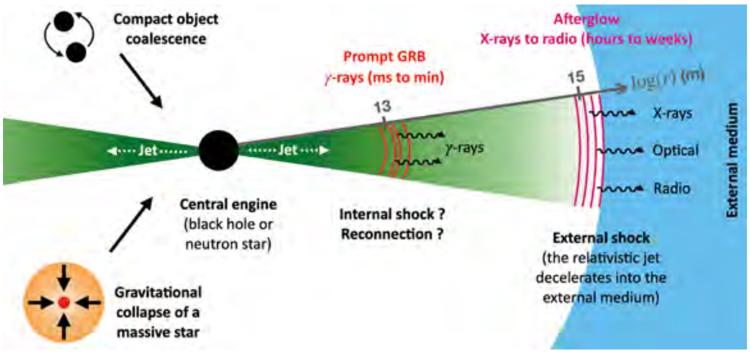

Figure 2. Model of the Gamma Ray Burst emission processes.

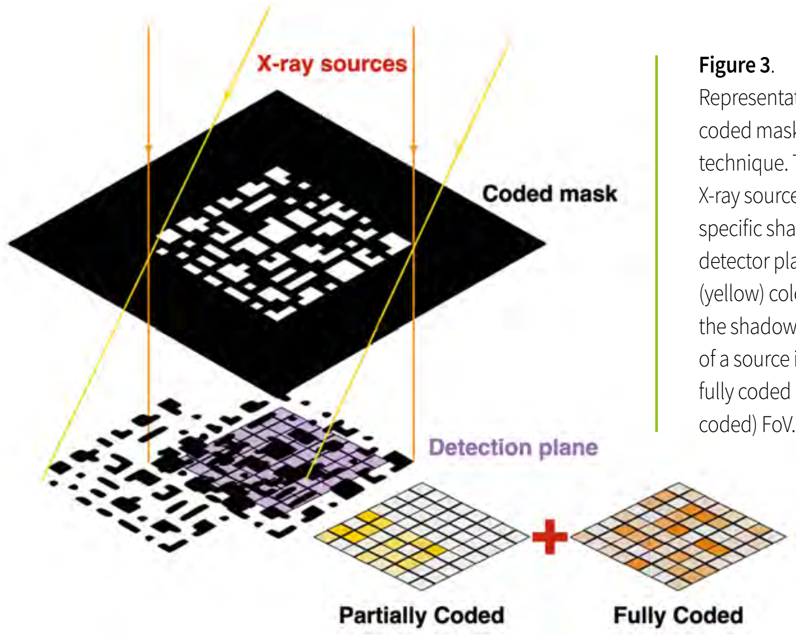

Figure 3. Representation of the coded mask imaging technique. Two X-ray sources cast a specific shadow on the detector plane. Orange (yellow) color illustrates the shadowgram of a source in the fully coded (partially coded) FoV.

tantalum foil of 0.6-mm thickness (Fig. 4). The mechanical resistance is achieved thanks to two titanium masks sandwiching the tantalum and firmly secured together with pins. Each of the titanium masks exhibits a large cross of 1.6-cm height in the centre, contributing significantly to the overall mechanical resistance of the final mask. Crucially, the design ensures that the titanium masks, including their crosses, do not interfere with the photons within the FoV of ECLAIRs as they traverse through the mask apertures.

The scientific pattern of the mask is divided into four independent quadrants of 23×23 (opaque or transparent) elements. The choice of the size of the holes (~11 mm-side squares) is determined by the requirement that the localisation error provided by ECLAIRs for triggered GRBs must be smaller than the FoV of the VT instrument onboard SVOM, which is equal to 26×26 arcmin^2. This ensures that the triggered GRB is in the VT's FoV after repointing the satellite in the source direction. The mask aperture (ratio of the surface of the transparent elements to its total surface) is 40% which has been shown by simulations to be a trade off to have a good mechanical resistance and a good sensitivity to GRBs.

Due to its large FoV and a large fraction being partially coded, the choice of a random pattern was imposed (see insert 2). A dedicated algorithm has been developed to generate and control the growth of the mask elements to ensure that the pattern is compatible with the self-supporting constraint (*i.e.* the final pattern can be obtained by simply digging holes in a foil). To improve the resistance, holes were connected to other holes only by their edges and not by their corners. Due to these constraints, even if their design involves a random generative process, such patterns are called pseudo-random patterns. 600,000 23×23-element patterns were generated and their response simulated. To build the four quadrants, we selected the four patterns with the best sensitivity respecting the localisation constraints. Detailed mechanical simulations have then shown that a few elements were reducing locally the mechanical resistance and have been simply moved manually to allow the final design to meet the requirements.

CONCLUSIONS AND PERSPECTIVES

After its launch, SVOM will enter a commissioning phase, marked by instrument start-up, testing and calibration. These preliminary stages are crucial for guaranteeing data reliability and paving the way for future scientific exploitation. The first results from ECLAIRs could be available by the end of 2024, offering an unprecedented perspective on the cataclysmic Universe. While hard X-ray energies have traditionally served to monitor the transient sky due to the capacity to build large FoV coded mask instruments, observing in this energy

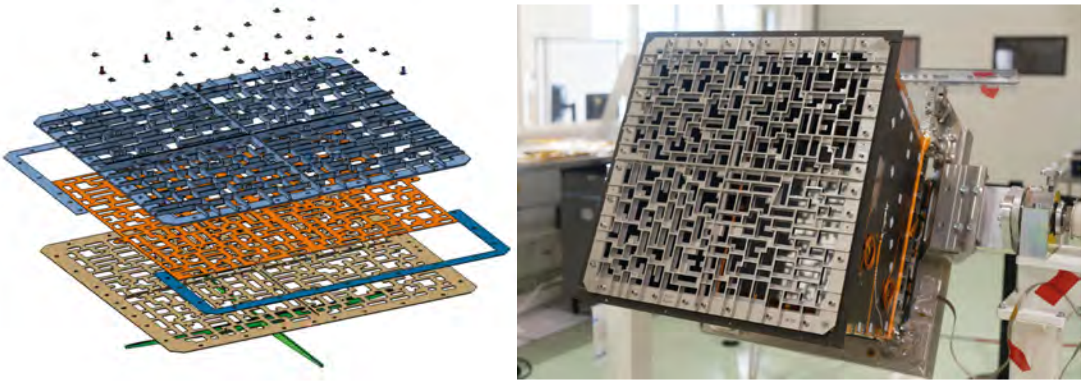

Figure 4. Left: Schema of the different parts of the mask. The tantalum mask is represented in orange and all other components are made of titanium. Credit: SVOM/APC. Right: Image of the ECLAIRs flight model during the integration process at CNES. Taken with permission from CNES.

band has a cost since it excludes the highly redshifted sources whose photon energy falls below the energy threshold of the instruments. In contrast, in the soft X-ray range (0.2 to 10 keV), a new generation of instruments, whose optical design mimics the lobster's eye, has been recently developed. These new X-ray optics consist of micro-channel plates arranged in a spherical configuration, effectively focusing light onto detectors while providing a significantly wider FoV compared to traditional optical configurations [5]. Such innovation presents exciting opportunities for monitoring the transient high-energy sky. Notably, instruments like the MXT onboard SVOM and the recently launched Einstein Probe satellite are pioneering this new optical approach, marking a significant advancement in astrophysical transient observing capabilities. ●

DECONVOLUTION OF THE DETECTOR IMAGE

The recorded detector image consists of a background together with the superposition of the shadowgrams produced by each source in the FoV. A reconstructed image of the sky is built by correlation between the detector image D and a decoding matrix G obtained from the coded mask pattern. If M is a matrix representing the mask with transparent (opaque) elements described by values equal to one (zero), then D is the correlation of the sky image S with M, to which is added the background noise B such as: $D = S \star M + B$. Hence, the sky image S' can be reconstructed by applying the decoding matrix G: $S' = D \star G = S \star M \star G + B \star G$. The reconstruction quality therefore depends on the choice of M and G. It is essential that, in absence of noise, there is a one-to-one correspondence between S and S′, *i.e.* that $M \star G = \delta$. On the other hand, it is desirable that the effect of noise appears uniformly in the deconvoluted image. Mask patterns M, satisfying these two conditions, are called optimal patterns. In such a case, if the background B is flat, then $B \star G$ is constant and can be easily removed. Uniformly Redundant Arrays (URAs) and their generalisations (*e.g.* Modified Uniformly Redundant Array ones - MURA patterns) were shown to be optimal for imaging which means that the point source response function of the telescope has a side-lobe-free central peak. Such an ideal response can be obtained due to the cyclic nature of the mask pattern and this only happens for sources in the fully coded FoV [4]. On the contrary, sources outside the coded FoV will produce secondary lobes a.k.a. coding noise in the reconstructed images. In this context, even if they do not produce ideal response for imaging, random mask patterns are often chosen since they do not limit the FoV of the instrument contrary to optimal cyclic patterns.

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