

A focusing telescope for gamma-ray astronomy

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Abstract

With the development of the Laue Lens, gamma-ray astronomy is presently realizing the step that virtually all branches of astronomy have accomplished since Lippershey's invention 400 years ago: the focusing telescope. In a Laue lens, gamma-rays interact coherently inside a crystal via Bragg-diffraction; a large number of diffraction crystals are oriented in a way to deviate incident photons onto a common focal spot. With its unprecedented sensitivity, angular- and energy-resolution, a mission featuring a Laue lens addresses a wide range of fundamental astrophysical questions such as the life cycles of matter and the behavior of matter under extreme conditions.

Introduction

Since the wavelength of nuclear gamma-ray photons is two to three orders of magnitude shorter than the distance between atoms in solids, astrophysicists are used to accepting that it is "impossible to reflect or refract gamma-rays". Consequently, the telescope concepts in nuclear astrophysics do not employ mirrors or lenses; they are based on inelastic interaction processes making use of geometrical optics (shadowcasting in modulating aperture systems such as coded masks) or quantum optics (kinetics of Compton scattering).

These instruments are now reaching the physical limits for space missions and have lead gamma-ray astronomy to an impasse where "bigger is not necessarily better". Improvements in the sensitivity of an instrument can usually be obtained by a larger collection area - in the case of traditional gamma-ray telescopes this involves a larger detector surface. However, since the background noise is roughly proportional to the volume of a detector, a larger photon collection area is

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synonymous with higher instrumental background. The sensitivity is thus increasing at best as the square root of the detector surface.

This mass/sensitivity dilemma can ultimately only be overcome if gamma-ray astronomy finds a way of achieving what virtually all branches of astronomy have accomplished since 1609 : focusing !

The principle of the Laue lens

In a Laue diffraction lens, crystals are disposed on concentric rings such that they will diffract the incident radiation of a same energy onto a common focal spot. In order to be diffracted, an incoming gamma-ray must satisfy the Bragg relation

$$2 d \sin \theta_B = n \lambda \quad (1)$$

where d is the crystal plane spacing, θ the incident angle of the photon, n the reflection order, and λ the wavelength of the gamma-ray.

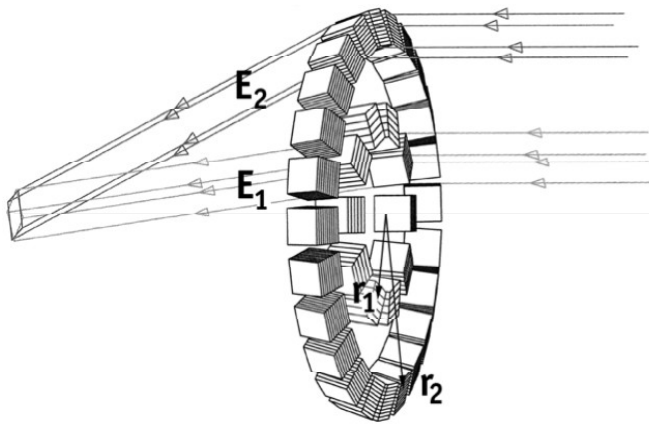


Fig. 1
The basic design of a Laue lens

The energy band of a ring of crystals is proportional to the square of the diffracted energy

$$\Delta E \approx 2dE^2 / \Delta\theta n h c \quad (2)$$

here, $\Delta\theta$ is the mosaic width of the crystal, i.e. the angular range over which the crystals reflect monochromatic radiation.

First Light for the Laue Lens

The objective of the R&D project CLAIRE was to prove the principle of a Laue lens under space conditions and on an astrophysical target.

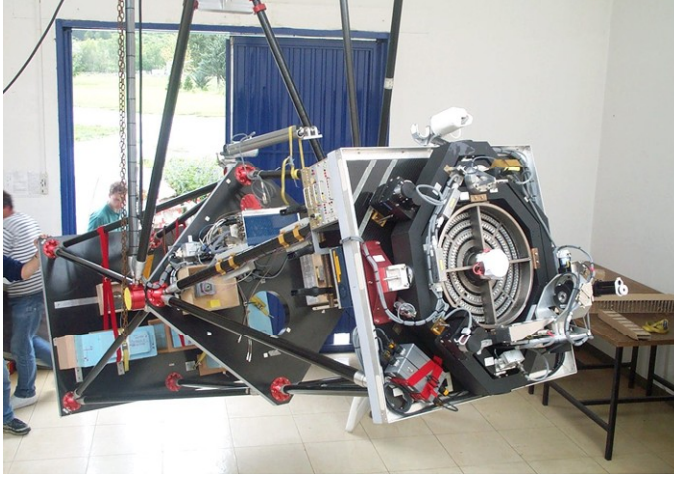


Fig. 2 : The CLAIRE telescope at Gap during the 2001 balloon campaign. On the first platform, the gamma-ray lens in its two-axes gimbal.

CLAIRE features a Laue lens consisting of Ge-Si mosaic crystals, focusing gamma-ray photons from its 511 cm² area onto a small array of cryogenic germanium detectors. The diffracted energy of 170 keV results in a focal length of 279 cm and the energy bandpass is about 3 keV. The balloon gondola demonstrated its ability to stabilize the lens to a few arcseconds; the entire payload weighs 500 kg.

The astrophysical target was a “standard candle”, the Crab nebula; the data analysis is described in detail in Halloin et al. 2004.

CLAIRE’s first light consists of an excess of 33 diffracted photons from the Crab, corresponding to a 3 s detection and a peak efficiency of ~ 10%.

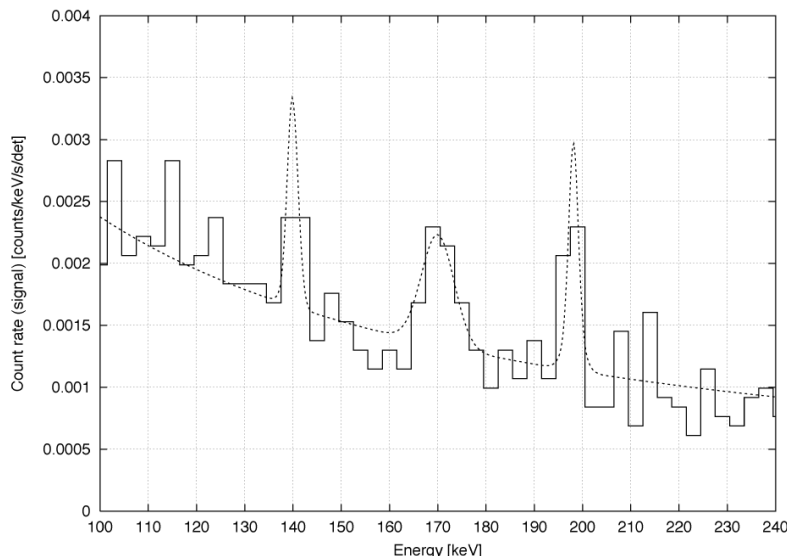


Fig. 3 *The flight spectrum for single events recorded during 72 min with good Crab pointing shows an excess of 33 photons at 170 keV – CLAIRE's first light !*

To confirm the results of the flight and to validate the relationship between distance and diffracted energy, a 205 m long test range was set up at an aerodrome at Ordis near Figueras, Spain (Alvarez et al., 2004). The X-ray source consisted of an industrial X-ray generator. The results of the CLAIRE flight and long distance test validate the theoretical models and demonstrate the potential of a gamma-ray lens for nuclear astrophysics.

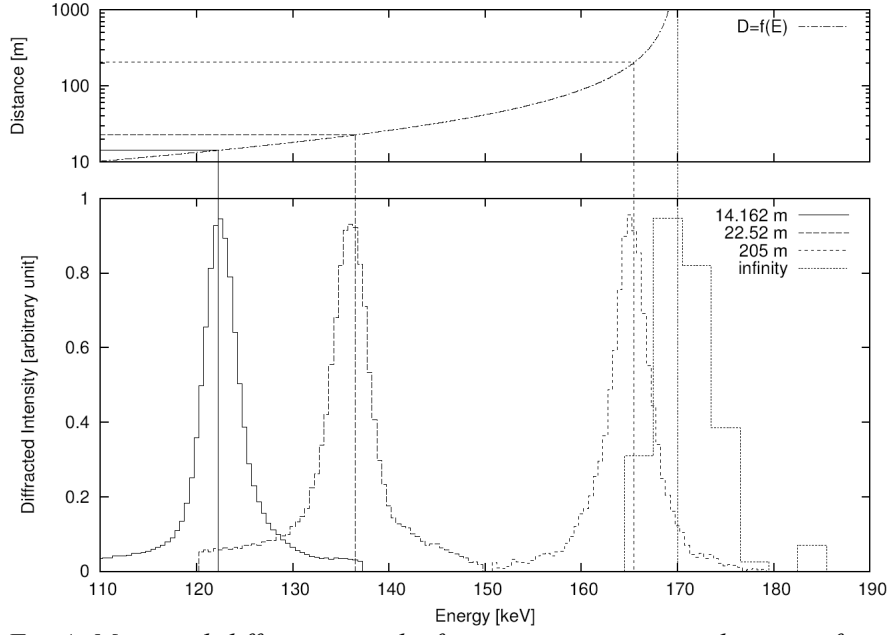


Fig 4. Measured diffraction peaks for sources at various distances from 14 m, 22.5 m (CESR), 205 m (CLAIRE TGD) and "infinity" (the Crab during the CLAIRE 2001 balloon flight)

The Science Case

Nuclear astrophysics addresses a wide range of fundamental astrophysical questions such as the life cycles of matter and the behavior of matter under extreme conditions.

Supernovae : Type Ia supernovae (SN Ia) are among the most spectacular explosive events in the Universe. They are major contributors to the production of heavy elements and hence a critical component for the understanding of life cycles of matter in the Universe and the chemical evolution of galaxies. The great brightness of SN Ia has made them a valuable tool for the measurement of extragalactic distances and for determining the shape of the Universe. Because they allow the direct observation of radioactive isotopes that power the observable light curves and spectra, gamma-ray observations of SNe Ia that can be performed with a Laue lens are in a position to make a breakthrough on the detailed physical understanding of SNe Ia, important for its own sake, and also necessary to constrain systematic errors when using high- z SNe Ia to determine cosmological parameters.

High resolution gamma-ray spectroscopy provides a key route to answering these questions by studying the conditions in which the thermonuclear explosion starts and propagates. A sensitivity of 10^{-6} photons $\text{cm}^{-2} \text{s}^{-1}$ to broadened gamma-ray lines allows observations of supernovae out to distances of 50–100 Mpc. Within this distance there will always be a type Ia SN in the phase of gamma-ray line emission, starting shortly after explosion, and lasting several months.

Positron astrophysics : Positron production occurs in a variety of cosmic explosion and acceleration sites, and the observation of the characteristic 511 keV annihilation line signature provides a powerful tool to probe plasma composition, temperature, density and ionization degree. The positron annihilation signature is readily observed from the galactic bulge region yet the origin of the positrons remains mysterious. Compact objects - both galactic and extragalactic - are

believed to release significant numbers of positrons leading to 511 keV gamma-ray line emission in the inevitable process of annihilation.

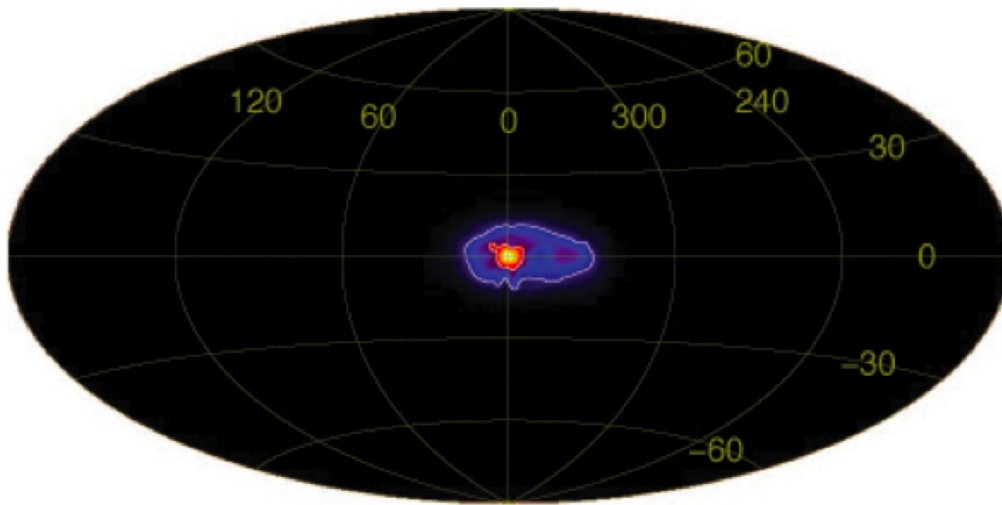


Fig. 5 INTEGRAL/SPI skymap of 511 keV gamma rays from e^+e^- annihilation. The emission can be seen to be extended towards the right-hand side of the map.

A recent SPI/INTEGRAL all-sky map (Weidenspointner et al. 2008) of galactic e^-e^+ annihilation radiation suggests that about half - and possibly most - of the positrons are coming from galactic X-ray binaries. The claim stems from an asymmetry of the 511 keV emission resembling an asymmetry in the distribution of low mass X-ray binaries with strong emission at photon energies > 20 keV ('hard' LMXBs).

Numerous problems surrounding the nature of galactic compact objects could be elucidated by the study of annihilation features with a high sensitivity / high resolution gamma-ray telescope : Are LMXBs really contributing to the narrow annihilation line? Do the spectra of other compact objects, such as galactic microquasars, show annihilation features ?

A DUAL mission concept

The scientific objectives for nuclear astrophysics include compact sources such as local supernova, galactic and extragalactic compact objects, long-lived galactic radioisotopes with hotspots possibly in the degree range, but also the extremely extended galactic disk and bulge emission of the narrow e^-e^+ line.

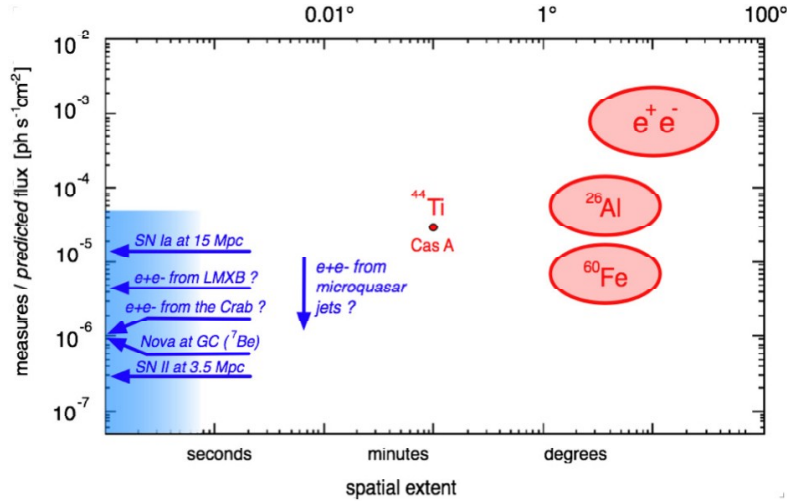


Fig 6 : A future gamma-ray mission has to face emissions with a wide range of angular extent, and with intensities different by several orders of magnitude

The requirements naturally can be divided into two subsets: a requirement for medium-sensitivity large-scale exposures, and very deep pointed observations. This duality is naturally addressed by the DUAL mission concept, which employs a wide-FoV Compton telescope (CAST) performing deep all-sky surveys in combination with a Laue-lens (LLT) that enables simultaneously very deep observations of selected narrow-field targets, utilizing the CAST Compton camera as its focal plane.

Formation flying and orbital constraints are virtually identical to those validated by the CNES/PASO study of the MAX mission concept.

The **Compton All-Sky Telescope** is a Japanese small satellite mission concept, presently in a prephase-A study at JAXA. CAST is a wide FOV Si/CdTe Compton Telescope based on the SGD (Soft Gamma-ray Detector) on board the Japanese Astro-H mission (Takahashi et al 2006). Over its lifetime, CAST will produce all-sky surveys in the energy range of 60 keV to 2 MeV: mapping out in detail the extended distributions of galactic e^-e^+ radiation, and of various long-lived cosmic radioactivities; surveying a very large sample of galactic and extragalactic compact sources by characterizing their nonthermal spectra.

Simultaneously to the all-sky survey of CAST, the **Laue-Lens Telescope** focuses on a number of selected compact sources, collecting gamma-rays from the large collecting area of its crystal diffraction lens onto a very small detector volume. With its outstanding narrow-line sensitivity of the order of $5 \cdot 10^{-7} \text{ ph s}^{-1} \text{ cm}^{-2}$ in the energy bands 450-520 keV and 800-900 keV, the focus of the LLT is on a comprehensive study of type Ia supernovae and on positron astrophysics.

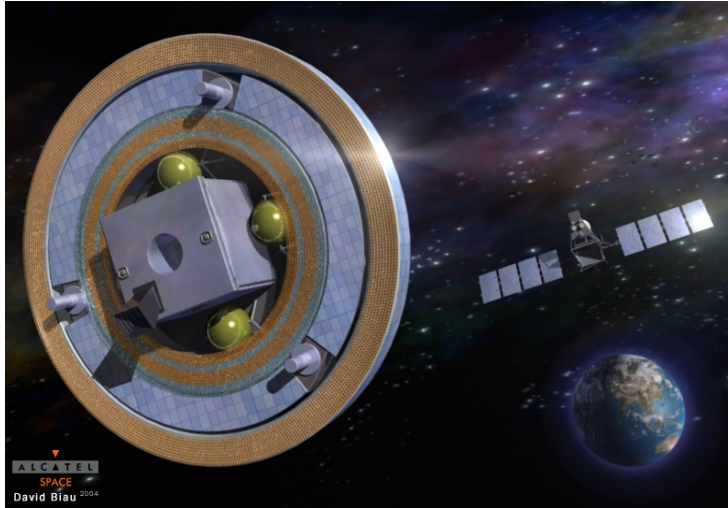


Fig. 7 Two separated spacecraft flying in formation will maintain the DUAL payloads at the focal length (92 m) by controlling the attitude to within about 1 cm³.

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