Performance of CLAIRE, the first balloon-borne gamma-ray lens telescope

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Abstract

CLAIRE is a balloon-borne telescope dedicated to validating the concept of a crystal diffraction lens for nuclear astrophysics. For the first time, focusing γ-rays enters into the domain of the high energy astrophysics. This represents a breaktrough in γ-ray instrumentation, and will allow unprecedent sensitivities. CLAIRE's first flights occurred on June 15 2000 and on June 14 2001. Here we present its performance during the two flights in terms of pointing accuracy, background noise and estimated efficiency of the lens.

Key words: Stratospheric Flights, Gamma Ray Spectroscopy, Instrumentation for Nuclear Astrophysics, Crystal Diffraction

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1 Introduction

Present telescopes for high energy astrophysics (from about 100 keV up to several MeV) make use of geometrical optics (shadowcasting) or quantum optics (Compton scattering). The main problem of these systems is that the collecting area is smaller or equal to the detecting area. Thus, the larger the collecting area, the higher the instrumental background, and, as a consequence, nuclear astrophysics has reached something of a dead end where bigger is not necessarily better.

2 Description of the lens

One possible way to overcome this obstacle consists of focusing γ-rays from a large collecting area onto a small detector, exactly as it is usually done with less energetic photons. If this can be done, the background noise can be extremely low, making unprecedented sensitivities possible. Yet, due to the high energy of γ-ray photons, they are usually either absorbed or incoherently scattered passing through matter and focusing has been considered impossible for a long time.
Nevertheless, γ-rays interact coherently inside a crystal lattice, provided that the angles of the incident photons are very small. This has led us to developing a lens using Bragg difraction. The small angles of scattered photons and the high power of penetration of gamma rays in matter led us to choose the so-called Laue geometry. This means that photons propagate through the entire crystal, using all the crystal thickness for diffraction. In order to be diffracted, an incoming γ-ray must satisfy the Bragg relation : $2d\sin(\theta) = n\lambda$. where d is the crystal plane spacing, θ the incident angle of the photon with respect to the crystal planes, n the reflection order, and λ the wavelength of the γ-ray. Based on this principle, the first γ-ray lens for astrophysics has been built by mounting germanium-silicon crystals in concentric rings. Using the small angle approximation and the Bragg relation, the radius, R, of each ring is proportional to $\frac{D}{Ed}$, where E is the energy of incident γ-rays and D is the focal length. Thus each crystal has to be tuned (i.e. oriented in order to obtain the correct scattering angle θ) so that for a source at infinity all incident photons of a chosen energy are focused on the same focal point. By differentiating the Bragg relation, the energy band of a γ-ray lens is seen to be proportional to the square of the diffracted energy :

$$\Delta E \approx \frac{2dE^2\Delta\theta}{hc} \Leftrightarrow \Delta E \approx 40.0 \left(\frac{d}{d_{Ge[111]}}\right) \left(\frac{E}{511keV}\right)^2 \left(\frac{\Delta\theta}{1arcmin}\right) \; keV(1)$$

where $\Delta\theta$ is the *mosaic width* of the crystal, i.e. the angular range over which the crystal reflects monochromatic radiation.$\Delta\theta$ is also an indication of the field of view of the lens.
Consequently, the main characteristics of optics using crystal diffraction lie in a narrow energy band (typically a few keV) and a small field-of-view (about 1 arcmin). After testing the principle of a γ-ray lens (Naya et al., 1996) on the ground, measuring the diffraction efficiency of GeSi crystals (Kohnle et al., 1998), CLAIRE is the next logical step towards a space borne crystal lens telescope. For more information about the design and objectives of CLAIRE, please refer to Laporte et al. (2000).

3 The CLAIRE project

The diffraction lens is dedicated to the observation of nuclear lines. However, given the the relative short exposure time on stratospheric flights and since no strong enough γ-ray line source in the range up to a few hundred keV has been firmly established yet, an acceptable alternative was the continuum in a narrow energy band of the well-known Crab nebula and pulsar. The first γ-ray lens was tuned for a diffraction energy of 170 keV, corresponding to a 2.79 m focal length for our 45 cm diameter lens. According to eq. 1, this leads to a energy band of about 3 kev for a 50 arcsec mosaic width.
The first two flights of CLAIRE occurred on June 15 2000 and June 14 2001. CLAIRE was launched from the CNES launch site at Gap in the French Alps (South-East of France) and landed close to the Atlantic coast (in the South-West of France) about 600 km away. For both the two flights, the launch took place in the middle of our launch window. Float altitude (respectively 40 and 41.5 km for the first and second flights) was reached after about 2.5 hours and lasted between 5 and 6 hours.
The first flight showed that the required pointing accuracy is feasible on a balloon. Yet, as might have been expected for the first flight of such a complex system, it took some time to optimise and calibrate the pointing system in flight conditions. A technical problem also prevented us from correctly pointing the Crab nebula more than about 1 hour. Given the relatively high background noise in the passively shielded detectors, the Crab nebula was not significantly detected. Nevertheless, the detector background lay within 20% of our prediction - this is at a measured level of $1.3 \cdot 10^{-3}$ cts$\cdot$cm$^{-3}\cdot$s$^{-1}\cdot$keV^{-1} at 170 keV.
Operation during the second flight appears to have been entirely nominal despite a flight duration shorter than expected (5h15 at float altitude with 3h40 of good pointing time, see section 5.2).

Fig. 1. CLAIRE during pointing tests at the launch site.

4 The CLAIRE telescope

The lens module, detector package, and pointing systems are integrated into an purpose designed telescope structure made of composite materials (See Figure 1). The structure was designed, manufactured and tested by the University of Birmingham. The upper platform holds the lens and its fine pointing system (see section 5.2). The detecting systems (detector matrix, dewar, collimator and electronics) are mounted on the lower platform.

The γ-ray detector consists of a 3x3 high purity Ge matrix. Each of the 9 elements is a 1.4 cm x 1.4 cm x 4 cm n-type coaxial detector with an central hole of 0.5 cm diameter x 3.5 cm (detector volume : 7.15 cm^3). The detector, surrounded by its two stages of side shielding (2001 configuration) is shown on Figure 2. The detector matrix is cooled by a liquid nitrogen dewar, kept at constant pressure during the flights. The focal spot ideally is on the central detector of the 3x3 Ge-matrix, but during flight the spot may wander around on the Ge-detector as the primary stabilization seeks its central position (see section 5.2). The 9 detectors are hereafter identified by their number, from 1 for the upper left detector to 9 for the lower right one. During the two flights, all 9 Ge detectors showed nominal performances with practically no line shifts.

The lens in itself is composed of several hundreds crystals mounted on a titanium frame developped at the Argonne National Laboratory. The germanium-silicon used for the first two flights were grown by the Institüt für Kristallzüchtung

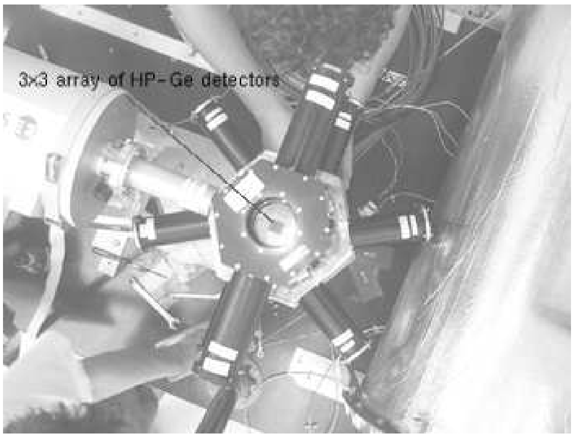

Fig. 2. The 3x3 HP-Ge matrix surrounded by the anticoincidence active shield.

and checked by the Institut Laue-Langevin.
For the second flight, several major improvements were made :

- Two additional rings had been filled up increasing the number from 6 to 8 and increasing the effective area from 41 cm^2 to 55 cm^2
- The detector was actively shielded to reduce the background noise
- An improved pointing system (designed by the CNES) with a wide field CCD, offsets mechanisms allowing a 7-days launch window and improved gondola stabilisation was used.

5 Analysis of the 2001 CLAIRE flight

5.1 Background analysis

The reduction of the background noise introduced for the 2001 flight is based on a activeanti-coincidence shield (ACS) and on the strictly flagging of events detected less than 50 ms after a failure of base line restoration (usually due to saturating events). Fig. 3 shows the recorded spectrum for single events in the whole matrix during flight at float altitude. The upper curve is the spectrum obtained with no background rejection and the lower one when ACS and delay after saturating events are taken into account. By this method the background noise is reduced by a factor of about 10 at 170 keV. After background rejection and in the range from 50 to 600 keV, only 4 background lines are significantly observable :

- Ge β decays lines : 53.44, 139.68 and 198.4 keV
- e^+-e^- annihilation line at 511 keV

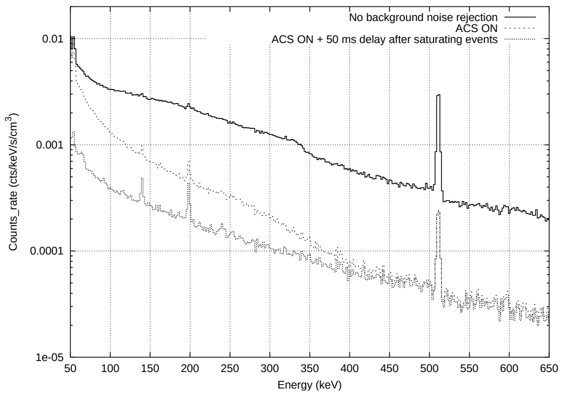

Fig. 3. Background spectra recorded at float altitude for single events

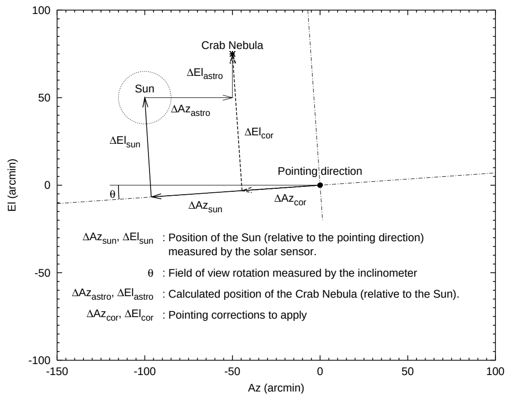

Fig. 4. Principle of the fine pointing system. The frame corresponds to the celestial reference, while the dot dashed lines represent the instrument (i.e. CCD camera) axes.

5.2 Pointing accuracy

The lens is mounted on a fine pointing system with a gimbal mount situated on the upper platform (see section 4). Around the 15^{th} of June, the Sun is very close to the Crab Nebula (about 1 deg) and so can be used as a guide star. A solar sensor with an offset mechanism was mounted on the lens frame. The absolute pointing requires also the knowledge of the field of view rotation, which was given by an inclinometer also mounted on the lens frame. The principle of fine pointing system is summarised in Fig 4. The solar sensor offsets were also checked by two CCD cameras, co-aligned with the lens, and giving the position of the Sun in their field of view.

Fig 5 represents the position of the Crab nebula, as seen by the lens, during the flight at float altitude. The lens FOV (about 80 arcseconds FWHM) is drawn with a bold dotted line. Each point represents the mean position of the Crab nebula during 1 s. The Crab pointing accuracy was better than 90 arcseconds during 3h30 with a pointing quality better than 35 arcseconds during 3/4 of this time.

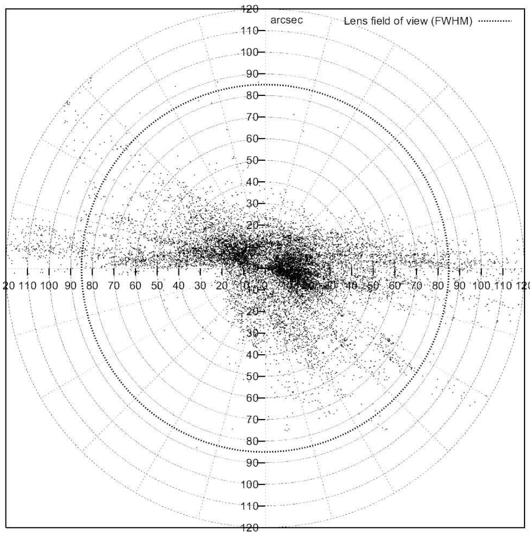

Fig. 5. Position of the Crab Nebula as seen by the lens at float altitude

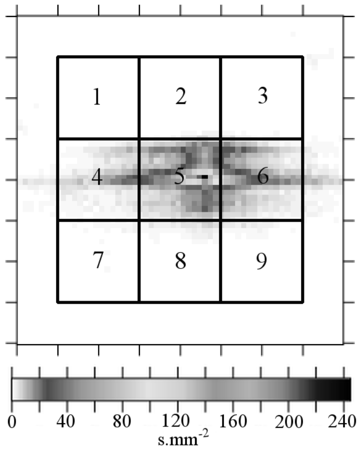

Fig. 6. Position of the focal spot on the Ge matrix during Crab pointing

The fine pointing system allows sufficiently accurate pointing of the lens axis relative to the sky. However, the position of the focal spot on the detector matrix depends on the primary pointing system. To keep the focal spot on the matrix, or on the central detector requires a primary pointing accuracy of ± 28 arcminutes, or of ± 9 arcminutes, respectively. Due to the imperfect stability of the azimuthal axis, the focal spot was mainly oscillating from the right (detector 4) to the left (detector 6) sides of the matrix with a period of 170 s. Fig. 6 is a cumulative 2D-histogram of the pointing time on the dectector matrix during the time when the fine pointing quality was better than 90 arcseconds. The focal spot appears to have been mainly between detector 5 and 6. Based on the (simulated) spatial distribution of the efficiency of the detectors and the point spread function of the lens, only single events with a focal spot located in a 1.4 cm diameter circle centered on a detector element have a high enough detecting probability to be useful.

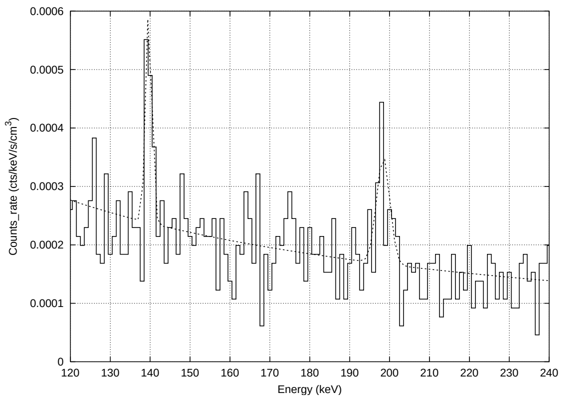

Fig. 7. Reduced spectrum for single events in det 5 and 6

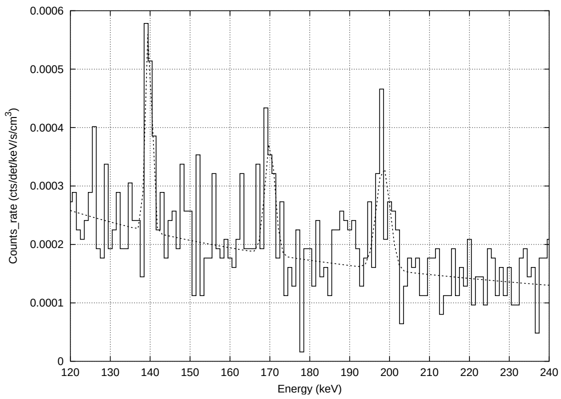

Fig. 8. Simulated reduced spectrum for single events in det 5 and 6

5.3 The search for signal

As usual in γ -ray astrophysics, the recorded spectra are dominated by background noise, mainly due to secondary emission induced by cosmic rays (e.g. N. Gehrels, 1992). In order to optimize the detectability of signal above background, it is necessary to carefully select good time intervals. As previously explained, one has to keep single events in time intervals for which the pointing quality was better than 90 arc seconds and the focal spot in a 1.4 cm diameter circle centered on detector 5 or 6. A preliminary spectrum resulting from this analysis is shown on fig 7. The diffracted signal from the Crab Nebula is expected as an additional gaussian peak at 170 keV. Simulations, making use of the achieved pointing and the diffraction efficiencies measured during the tuning of the lens show that about 40 events in detector 5 and 20 in detector 6 should have been detected. This number would lead to a 4.5-σ detection (see simulated spectrum on fig. 8).

It is apparent that there is no significant peak visible on the flight's spectrum. Some possible explanations can be put forward :

- The information given by the inclinometer (measure of the field of view rotation). However, this shouldn't be crucial since an error of 1 deg in field of view rotation results in only about 2 arcmin error in Crab pointing.

- The focal spot may have shifted with respect to the detector due to mechanical deformations during the flight.
- For a still unknown reason the efficiency of the lens at 170 keV (for a parallel polychromatic beam) may have been lower than the prediction calculated from measures at 122 keV, which were made with divergent polychromatic and monochromatic beams.

These items are presently under studies. Especially, the lens is being tested on its tuning bench at the CESR in order to validate the diffraction models used for the 2001 flight. We are quite confident that these investigations will shed new lights on the results of the CLAIRE 2001 flight.

6 Conclusion

Despite the fact that no significant signal has so far been detected, the first two flights of CLAIRE demonstrated that testing the γ-ray lens on a stratospheric balloon is feasible. The pointing systems achieved very good accuracy, whereas the actively shielded detectors showed low background noise for a stratospheric flight. The CLAIRE payload is presently being upgraded and is scheduled for a transmediterranean balloon flight in June 2003. After having demonstrated the gamma-ray lens as a tool for nuclear astrophysics, further balloon flights could use a lens tuned for higher energy - e.g for the study of the 511 keV annihilation line.
Ultimately, the crystal diffraction lens will be put in space where longer exposures, longer focal length and steady pointing will result in outstanding sensitivities. A space borne crystal telescope will use a gamma ray lens situated on a 3-axes stabilised spacecraft, focusing gamma rays on a small HP-Ge detector. The detection system would be put on another small spacecraft, stabilised to a precision of 1 cm^3, about 130 meters behind the lens. Made of two large Cu and Ge rings (respectively 176 cm and 222 cm diameters) such a crystal lens will observe in two 100 keV wide energy ranges around 500 keV and 850 keV, with a sensitivity of a few 10^{-7}photons$\cdot$s$^{-1}\cdot$cm^{-2}.

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