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CLAIRE – towards the first light for a gamma-ray lens

P. Laporte[a], N. Abrosimov[b], P. Bastie[c], B. Cordier[d], G. Di Cocco[e], J. Evrard[f], L. Gizzi[e], B. Hamelin[g], P. Jean[a], Ph. Laurent[d], P. Paltani[h], G.K. Skinner[b], R.K. Smither[i], P. von Ballmoos[a,*]

[a]*Centre d'Etude Spatial des Rayonnements, 9 avenue du Colonel-Roche, 31400 Toulouse, France*
[b]*University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK*
[c]*Institut fr Kristallzchtung, Berlin-Adlershof, Germany*
[d]*SAp, CEA-Saclay, CEA-SAP, 91191 Gif-sur-Yvette Cedex, France*
[e]*TESRE, Via P. Gobetti, 101, 40129 Bologna, Italy*
[f]*CNES, 18 avenue Edouard Belin, 31041 Toulouse, France*
[g]*Institut Laue Langevin, rue des Martyrs, BP 156, 38042 Grenoble, France*
[h]*ISDC, Chemin d'Ecogia 16, 1290 Versoix, Switzerland*
[i]*ANL, 9700 South Cass Avenue, Argonne, IL 60439, USA*

Abstract

The CLAIRE collaboration is presently preparing the first astronomical observation of a gamma-ray lens. In June 2000, the instrument is to be flown on a stratospheric balloon by the French Space Agency CNES. CLAIRE features a Laue diffraction lens, a detector module with a 3×3 germanium array, and a balloon gondola stabilized to 15″ pointing accuracy. The instruments lens focuses gamma-ray photons from its 526 cm^2 area onto a small solid-state detector, with only 18 cm^3 equivalent volume for background noise. Hence, for the first time in gamma-ray astronomy, the statistics will be dominated by the signal. Besides its excellent sensitivity, the telescope has outstanding angular and spectral resolution. The primary objective for the first balloon flight of CLAIRE is to detect the Crab nebula and measure its extend at 170 keV with an angular resolution of about 1 arcmin. Scientific objectives for further flights include collapsed objects, SNRs, and broad class annihilators.

Keywords: Instrumentation for nuclear astrophysics; Crystal diffraction

1. Introduction

Present telescopes for nuclear astrophysics make use of geometrical optics (shadowcasting in modulating aperture systems) or quantum optics (kinetics of Compton scattering). Because the collecting area of such systems is identical to the detector area, nuclear astrophysics has come to an impasse where bigger is not necessarily better: with the background noise being roughly proportional to the volume of a detector, a larger photon collection area is synonymous with higher instrumental background – consequently, the signal-to-noise ratio does not improve with the larger collectors.

* Corresponding author. Tel.: 05-61-55-66-47; fax: 05-61-55-6651.
E-mail address: pvb@cesr.fr (P. von Ballmoos)

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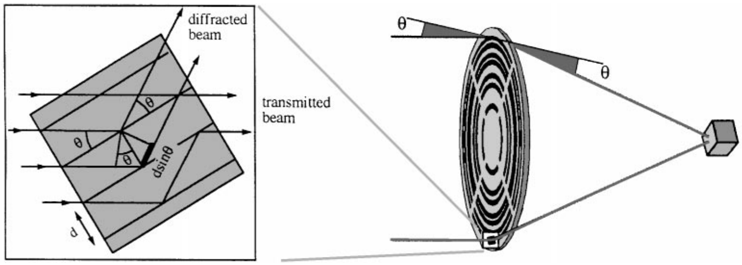

Fig. 1. The basic design of a focusing γ-ray telescope: the lens consists of quasi perfect single crystals arranged in concentric rings; γ-rays are focused into a common focal spot by Bragg reflection in Laue geometry (θ is the Bragg angle, see Eq. (1)).

One possible way out of this impasse consists of taking advantage of the phase information of the photons. γ-rays can interact coherently inside a crystal lattice provided that angles of incidence are very small. As a consequence of the small scatter-angles and the high penetration power of γ-rays one makes use of Bragg diffraction in Laue geometry (Fig. 1): γ-rays are focused from a large collecting area onto a small detector volume. As a consequence, the background of a crystal diffraction telescope is extremely low, making possible unprecedented sensitivities. Today, Laue diffraction lenses have demonstrated their potential in laboratory measurements up to several hundred keV [1–3].

While the evidence for point like sources of narrow γ-ray line emission has been mostly implicit at this point, various objects like galactic novae and extragalactic supernovae are predicted to emit detectable γ-ray lines. These sources should have small angular diameters but very low fluxes – mostly because such objects are relatively rare and therefore are more likely to occur at large distances. The instrumental requirements for exploring this class of sources match with the anticipated performance of a crystal diffraction telescope.

The characteristics of crystal diffraction telescopes (the fact that one observes in a narrow energy band of typically a few keV with a field of view of typically 15–60 arcsec and with virtually no background) can be exploited for a variety of observational aims: precise source localization, two-dimensional intensity mapping of sources with arc minute extent, the observation of narrow spectral lines, measurement of pulsar light curves in a narrow energy band. Yet, the concept of diffracting within a narrow energy band is best matched to the narrow lines in the domain of nuclear transitions (novae, supernovae). A tunable space borne crystal telescope will permit the observation of any identified source at any selected line energy in a range of typically 200–1300 keV. The sites of explosive nucleosynthesis are therefore a natural target for such an instrument: The nuclear lines of extragalactic supernovae (^{56}Ni,^{44}Ti,^{60}Fe) and galactic novae (e^-e^+line,^{7}Be) are accessible to observation, one at a time, since different decay times and changing opacity to γ-rays give rise to different lines being dominant at different times after the explosion. Other scientific objectives include the narrow 511 keV line from galactic broad class annihilators (such as 1E1740-29, nova musca), possible red-shifted annihilation lines from AGNs and annihilation afterglow of γ-ray burst counterparts, but also two-dimensional intensity mapping of strong continuum sources with unprecedented angular resolution. A list of possible scientific objectives is given in Table 1.

2. Principle of a diffraction lens telescope

A γ-ray lens consists of a frame on which concentric rings of germanium single crystals are mounted (Fig. 1). In order to be diffracted, an incoming γ-ray must satisfy the Bragg relation

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

where d is the crystal plane spacing, θ the incident angle of the photon, n the diffraction order, and

Table 1
Potential scientific objectives for a γ-ray lens

Target class	Process	Example
Broad class annihilators	e^-e^+	1E1740.7 − 2942, GRS1758 − 258, Cyg X − 1 ...
Classical novae	^{7}Be, e^-e^+, ^{22}Na	GC novae (as N Cyg 1992)
Supernovae	^{57}Co, ^{56}Co, ^{44}Ti	Virgo SN Ia (as SN1991T)
X-ray binaries	e^-e^+ & NDL[a]	(as Nova Musca, Nova Persei)
Pulsars	e^-e^+ & NDL[a]	Crab, Vela, etc.
AGN	e^-e^+ & NDL[a]	NGC4151, 3C273, etc.
Solar flares	e^-e^+ & NDL[a]	
γ-ray burst afterglow	e^-e^+ & NDL[a]	Gamma-ray burst counterparts

[a]Detection of e^-e^+ annihilation line and nuclear de-exitation lines (NDL) may be possible if an estimate of cosmolocical and/or gravitational red shift is available.

λ the wavelength of the γ-ray. Thus, each ring uses crystals with a different set of crystalline planes. The radius R of each ring is optimized so that all crystals diffract the incident radiation to the same focal point. R, is given by the relationship

$$R = D \tan 2\theta \qquad (2)$$

where D is the focal distance. Thus the lens concentrates the radiation collected from a large area into a small focal spot. This allows a modest size, well shielded detector to measure a much larger signal than it would have intercepted if it was exposed to the radiation field directly.

Although the lens telescope in its present form is not a direct imaging system (one- or two-dimensional maps are produced by scanning the source region), the germanium detector array allows us to recognize an off axis source and, at limited distances, image the source.

After testing the principle of a γ-ray lens [3] on the ground and developing a very accurate (100 nm) feed-back loop to tune automatically each crystal [1]. CLAIRE is the next logical step towards a space borne crystal lens telescope.

3. The CLAIRE telescope

The purpose of CLAIRE is to demonstrate, for the first time, a γ-ray lens for astrophysical observations. The CLAIRE telescope, composed of a crystal diffraction lens and a solid-state detector matrix, is to be flown on a stratospheric balloon in June 2000. The development of a monochromatic focusing instrument offers its own outstanding scientific potential: even during the relatively short duration of a balloon flight a variety of observational aims can be achieved: precise source localization, two-dimensional intensity mapping of sources with arc minute extent and the observation of narrow spectral lines. Furthermore, as a proof of principle, a balloon telescope is a necessary step towards a space borne tunable instrument.

Our collaboration foresees a stepwise development of the balloon borne diffraction lens project: For the first balloon flight, we intend to observe the Crab Nebula with a lens tuned to energy 170 keV and a FWHM field of view of about 1 arcmin. Such a field of view will for the first time enable a mapping of the Crab nebula at low γ-ray energies. The detection statistics will be dominated by the source counts – for the first time in γ-ray energies where signal to background ratios have traditionally been in the percent range. The choice of a low-energy band (meaning small focal length) and a broader field of view for the first flight will lessen the demands on gondola pointing and telescope stabilization. The entire telescope is pointed with a precision of about 10 arcmin using conventional stabilization techniques of the gondola (magnetometers). Only the lens module, at a distance of 279 cm from the detector, is pointed with high accuracy ($\approx$ 15 arcsec) using a sunsensor.

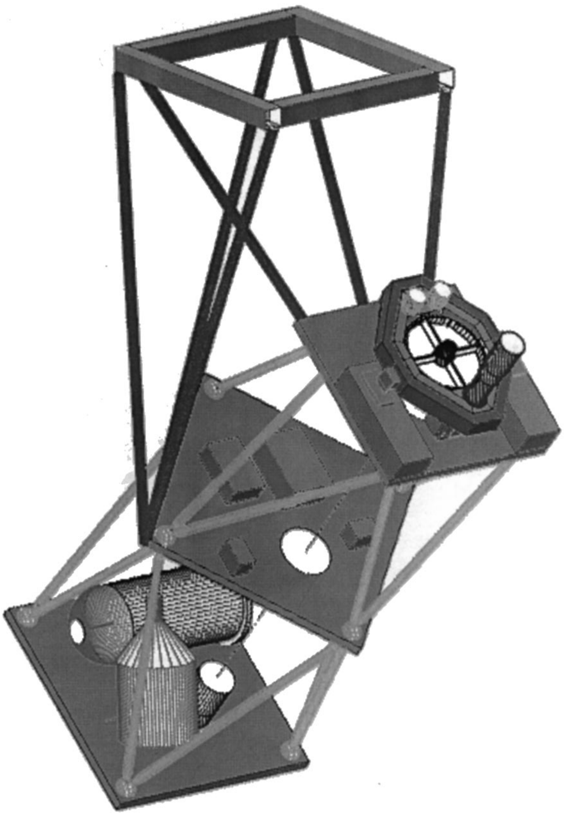

Fig. 2. The CLAIRE telescope.

CLAIRE's lens consists of 576 Ge(Si) crystals arranged in 8 rings. The footprint of the individual crystals (1×1 cm and 0.7×1 cm, respectively) results in a small focal spot ($\varnothing = 1.2$ cm). The goal is to place the focal spot on the central detector of our 3×3 HPGe matrix (element size $1.5 \times 1.5 \times 4$ cm) and to use the others for background rejection.

The lens module, detector package (3×3 Ge matrix, dewar and electronics), and fine pointing system are integrated into a telescope structure. Because of a restrictive mass budget, the CLAIRE gondola is mainly a pivot (Fig. 2). Compared to the laboratory models, tuning a lens for a balloon flight is more demanding since the incident beam from an astrophysical source is parallel.

(a) Whereas the tuning of a ground-based lens is relatively forgiving (from a calibration source at finite distance the diffraction crystal is seen under an angle of a few arcmin), here a crystal misorientation of a few arcsec decreases dramatically the diffraction efficiency. With a lever of only 10 mm to move the Ge(Si) crystal, 1 arcsec corresponds to a displacement of less than 100 nm.

(b) Since, we cannot directly calibrate the lens for 170 keV at infinite distance, we have to tune it on the ground using a source at a finite distance. We have chosen to use a continuum source (X-ray generator) at 14 m from the lens. As with an optical lens, the focal plane comes closer to the lens with a source at a finite distance. At this distance, a crystal will be correctly tuned if it diffracts an energy of 122 keV. In terms of energy, a misorientation of 5 arcsec represents a shift of 0.07 keV with respect to 122 keV. This configuration allows for verification in the field using a ^{57}Co source.

4. Performance and objectives

For an astrophysical source, the number of detected photons depends on the crystal properties and the detector efficiency. Using the numerical values in Table 2, we have calculated the performances for a Crab observation during a balloon observation. We have taken into account the atmospheric absorption (at an altitude of 40 km, the atmospheric depth is about 5 g cm^{-2}) and we assume an observation made around the Crab culmination. The Crab is expected to be measured with a signal to background ratio of 0.8–6.3, respectively for a passive and active shield (30 mm of BGO). We expect 32 γ's h^{-1} for a nebula size of 20 arcsec and 27 γ's h^{-1} for 40 arcsec.

The observation of this well-studied gamma-ray source will complete our knowledge of the telescope performance, in particular of the diffraction efficiency of the whole lens.

The maps of the Crab obtained with a scanning modulation collimator in the 22–64 keV energy range [4] indicate that the nebula size seems to decrease with increasing photon energy. With sufficient photon statistics, an instrument based on a gamma-ray lens, can constrain the extend of the Crab nebula at higher energies.

Successive flights will use a lens tuned to higher energies (line energies such as the 511 annihilation

Table 2
CLAIRE's characteristics and performances

Crystal lens	
Diffracting medium	576 Ge(Si) crystals in 8 rings 30 arcsec mosaic width
Diameter of frame	45 cm
Focal length	2.79 m
Diameter of focal spot	1.2 cm FWHM for continuum radiation
Field of view	78 arcsec for 170 keV
Energy bandwidth (on-axis)	1.0 keV FWHM
Effective collection area (170 keV)	115 cm^2
Detector matrix	
Detector type	9 HPGe n-type coaxial detectors, each element $1.5 \times 1.5 \times 4$ cm^3
Energy resolution	≈ 1.5 at 170 keV
Total detector area	20.25 cm^2
Efficiency at 170 keV	80%
Requirements	
Absolute pointing	Optical axis of the lens $\leq$ 15 arcsec
Telescope axis pointing	10 arcmin
Telescope system	
Energy range (on-axis)	170 ± 1.5 keV
Effective background volume	18 cm^3 (focal spot in central pixel)
Ratio of signal counts to BG counts	with active shield

line) and have a field of view as narrow as 15 arcsec. In this configuration (longer focal length, narrower beam) the instrument could help decide whether or not the recently discovered galactic micro-quasars are emitting a narrow e^-e^+ annihilation line.

5. Conclusion

The CLAIRE project is a high technological challenge: accuracies less than a micron are required to achieve a high sensitivity. For the Crab observation, we expect to be able to obtain the light curve in a narrow energy range and an estimation of the nebula extent. Observation data of this balloon flight will be very helpful in verifying the performance of an eventual satellite-based crystal lens telescope.

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