Available online at www.sciencedirect.com

SCIENCE DIRECT®

New Astronomy Reviews 48 (2004) 243–249

New Astronomy Reviews

www.elsevier.com/locate/newastrev

CLAIRE's first light

Peter von Ballmoos [a,*], Hubert Halloin [a], Jean Evrard [b], Gerry Skinner [a], Nicolai Abrosimov [c], Jose Alvarez [d], Pierre Bastie [e], Bernard Hamelin [f], Margarida Hernanz [d], Pierre Jean [a], Jürgen Knödlseder [a], Vincent Lonjou [a], Bob Smither [g], Gilbert Vedrenne [a]

[a] *CESR, 9, Av. du Colonel-Roche, 31028 Toulouse, France*
[b] *CNES, 18 Avenue Edouard Belin, 31401 Toulouse, France*
[c] *Institut für Kristallzüchtung, Rudower Chaussee 6, 12489 Berlin, Germany*
[d] *IEEC, Edif. Nexus, 08034 Barcelona, Spain*
[e] *Laboratoire de Spectrométrie Physique, BP 87, 38402 St Martin d'Hères, France*
[f] *Institut Laue-Langevin, BP 156, 38042 Grenoble, France*
[g] *Argonne National Lab, 9700 South Cass Avenue, Argonne, Il, 60439, USA*

Abstract

The objective of the R&D project CLAIRE is to prove the principle of a gamma-ray lens for nuclear astrophysics. CLAIRE features a Laue diffraction lens, an actively shielded array of germanium detectors, and a balloon gondola stabilizing the gamma-ray lens to a few arcseconds. On June 14 2001, the instrument was flown on a stratospheric balloon by the French Space Agency CNES; the astrophysical target was a "standard candle", the Crab nebula. CLAIRE's first light consists of ~33 diffracted photons from the Crab, corresponding to a 3σ detection. The performance of the gamma-ray lens during the balloon flight has been confirmed by ground data obtained at a 200 m long test range. Based on the diffraction efficiencies measured with CLAIRE, the mission concept of a space borne gamma-ray lens is proposed, and its potential for nuclear astrophysics is outlined.

PACS: 95.55.Ka; 95.85.Pw

Keywords: Gamma-ray optics; Instruments for nuclear astrophysics

1. Introduction

Present telescope concepts for nuclear astrophysics are based on inelastic interaction processes: they make use of geometrical optics (shadowcasting in modulating aperture systems) or quantum optics (kinetics of Compton scattering). Today these instruments are reaching the physical limits for space borne missions; moreover, several apparently unsolvable problems have lead gamma-ray astronomy to a mass-sensitivity impasse where "bigger is not necessarily better".

* Corresponding author. Tel.: +5-61-55-66-47; fax: +5-61-55-66-51.
E-mail address: peter.von-ballmoos@cesr.fr (P. von Ballmoos).

1387-6473/$ - see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.newar.2003.11.032

Improving the sensitivity of an instrument can usually be obtained by a larger collection area – in the case of "classic" gamma-ray telescopes this is achieved by a larger detector surface. Yet, since the background noise is roughly proportional to the volume of a detector, a larger photon collection area is synonymous with higher instrumental background. For "classic" gamma-ray telescopes, the sensitivity is thus increasing at best as the square root of the detector surface.

A possible way out of this dilemma consists of taking advantage of the phase information of the photons. Gamma-rays can interact coherently inside a crystal via Bragg-diffraction: the interference between the periodic nature of light and a periodic structure of matter in a crystal lattice. In a Laue diffraction lens, a large number of crystals are oriented in a way to deviate incident photons on a common focal spot: γ-rays are focused form a large collecting area onto a small detector volume. As a consequence, the background noise is extremely low, making possible unprecedented sensitivities.

As a first step, a ground-based prototype of a narrow band Laue lens system was built and successfully tested (Naya et al., 1996). Diffraction efficiencies of individual Ge crystals, measured at the APS synchrotron at Argonne National Laboratories agree with what is expected from the Darwin model (Kohnle et al., 1998) (efficiencies of 20–31% according to energy and crystal planes). The next logical step towards a space borne crystal lens telescope was CLAIRE: a project to demonstrate a crystal diffraction lens under space conditions and with an astrophysical target. In this article, the performance of CLAIRE on the ground and in flight is described. Extrapolating this performance to the case of a space-borne instrument reveals an outstanding potential for nuclear astrophysics: Laue diffraction lenses will achieve narrow line sensitivities of a few 10^{-7} photons s^{-1} cm^{-2} with high energy resolution ($E/\Delta E \approx 500$) and very good positioning.

2. Focusing gamma-rays

The small scatter-angles and the high penetration power of gamma-rays led us to choose Bragg-diffraction in Laue geometry, in which the photons traverse the crystal using its entire volume for diffraction. In a Laue type crystal 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 (Fig. 1). In order to be diffracted, an incoming gamma-ray must satisfy the Bragg-relation

$$2d \sin\theta_B = n\lambda, \tag{1}$$

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

A crystal at a distance r_1 from the optical axis is oriented so that the angle between the incident beam and the crystalline planes is the Bragg angle θ_{B1}; rotation around the optical axis results in concentric rings of crystals. With the same crystalline plane $[h\,k\,l]$ used over the entire ring, the diffracted narrow energy band is centered on E_1. In a *narrow bandpass Laue lens* such as CLAIRE, every ring of crystals uses a different set of crystalline planes $[h\,k\,l]$ in order to focus photons in a single energy band ($E_2 = E_1 = E_i$) onto a common focal spot.

For a given focal distance f of the lens, r_i is the radius of ring i,

$$r_i = f\tan[2\theta_{Bi}] \approx f\frac{n\lambda}{d_i}, \tag{2}$$

where n is the order of the diffraction process, d_i is the crystalline plane spacing of the i ring and λ is the wavelength of the radiation to be focused.

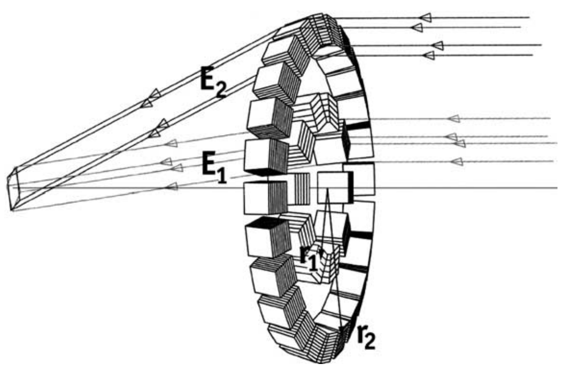

Fig. 1. The basic design of a crystal diffraction lens in Laue geometry.

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

$$\Delta E \approx \frac{2dE^2\Delta\theta}{nhc} \approx 40.0\left(\frac{d}{d_{\mathrm{Ge[111]}}}\right)\left(\frac{E}{511\ \mathrm{keV}}\right)^2\left(\frac{\Delta\theta}{1'}\right)\ \mathrm{keV}, \quad (3)$$

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

A narrow energy band is not a handicap when nuclear lines are to be observed, however, proving the principle on a balloon flight ironically implies observation of a continuum spectrum because the only available "standard candle" at γ-ray energies is the Crab nebula. The challenge of pointing a first balloon-borne lens makes a short focal length preferable; this excludes higher energies for the lens tuning. For CLAIRE, the diffracted energy band was more or less arbitrarily chosen to be 170 keV for a source at infinity.

3. CLAIRE

3.1. Instrument

CLAIRE features a narrow band-pass Laue diffraction lens, consisting of 556 germanium–silicon crystals mounted on eight rings of a 45 cm diameter titanium frame. The lens with its 511 cm^2 geometric area concentrates 170 keV photons onto a common focal spot (1.5 cm diameter) at a distance of 277 cm. Diffracted photons are collected on a small 3×3 array of high-purity germanium detectors, housed in a single cylindrical aluminum cryostat. Each of the single Ge bars is an n-type coaxial detector with dimensions of 1.5 cm $\times$ 1.5 cm $\times$ 4 cm. The detector matrix is cooled by a liquid nitrogen dewar that was pressurized during the flight. The detector is actively shielded by a CsI(Tl) side shield and BGO collimators. The CLAIRE stabilization and pointing system was developed by the balloon division of the French Space Agency CNES. Two almost independent pointing stages allow the observation of a target located within a few degrees of the sun (on June 14 and 15 the Crab is within 1° from the sun): the primary pointing system stabilizes the entire telescope to within 10 arcmin; the fine pointing system is based on a gimbal, it is capable of pointing the γ-ray lens alone with a precision of a few arcsec. The 3 m telescope structure consists of carbon fiber spars and honeycomb platforms; the entire payload weighs 500 kg.

3.2. Balloon flight

On June 14, 2001, CLAIRE was launched by the French Space Agency CNES from its base at Gap-Tallard in the French Alps, and was recovered, after nearly 6 h at float altitude (3 mbar), close to Bergerac in the Southwest of France. All nine germanium detectors showed nominal performance during the flight, the energy resolution at 170 keV was about 2.5 keV FWHM. The anticoincidence shield reduced background noise by a factor of 10, resulting in a continuum of about 2.3×10^{-4} cts $\mathrm{s}^{-1}\,\mathrm{keV}^{-1}\,\mathrm{cm}^{-3}$ at 170 keV for single events (see Fig. 2(a)) – four background-lines dominate the continuum: three Ge isomeric transitions (53.4, 139.7 and 198.4 keV) and the e^-e^+ annihilation line (511 keV). To ensure the operation of the lens, its temperature was kept within a range that corresponded to the interval experienced in the laboratory. Before and after the flight, the overall diffraction efficiency of the lens was verified with a ^{57}Co source, at a distance of 14 m from the lens on the optical axis. In spite of a rough parachute landing and recovery, the two tests showed virtually identical efficiencies ($\sim$7% at 122 keV, assuming a mean mosaicity of 70″).

3.3. Data analysis

Given the amplitude of the lens-axis oscillations, the fine pointing quality of the Crab seemed to be better than 90″ during 3.5 h (90″ corresponds to the field of view of the lens). Likewise, the amplitude of the excursions of the focal spot on the detector were smaller than the width of the Ge matrix. A comprehensive simulation of the observation (Crab spectrum, atmosphere, flight- and pointing-data, lens reflectivity,

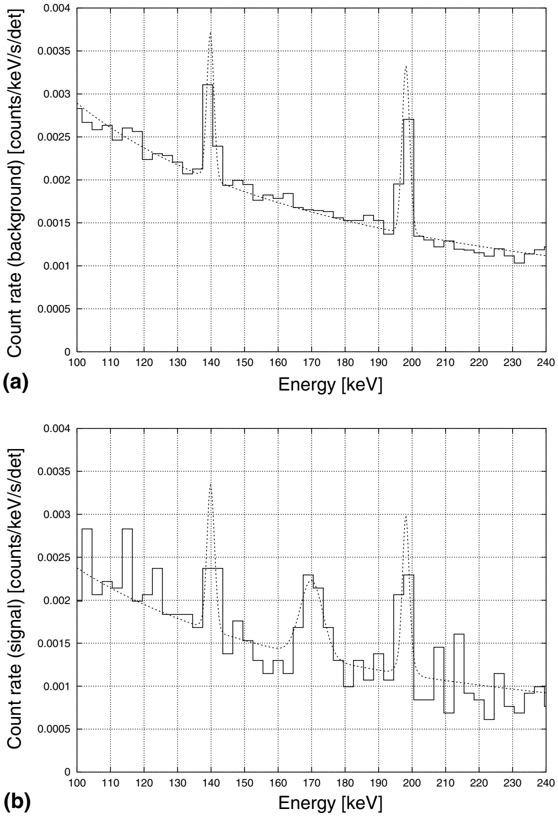

Fig. 2. (a) Spectrum for single events at float altitude (background noise spectrum); (b) reduced spectrum for single events recorded during time intervals with good Crab pointing at 170 keV, an excess of 33 photons is detected.

detector efficiency) showed that a 4.5σ detection was expected. Nevertheless, an initial data analysis did not result in a positive detection of the Crab (Halloin et al., 2003). The key for finding a signal turned out to be the discovery of an *offset* of the lens axis, both in the fine pointing system (the Crab pointing) as well as in the primary pointing system (position of the focal spot on the detector). The offset in the Crab pointing was due to a prismatic effect in the CCD's sun-filter. We were able to measure the direction and amount (70″) of the effect a posteriori in our laboratory. Reassembling and testing the telescope structure revealed that the focal point moves by 4.5–6 mm when in the observing position, and that its position in the X-axis is indeterminate to within a range of about −15 and 15 mm. An exhaustive discussion of CLAIRE's primary and fine pointing is given by Halloin et al. (in press).

3.4. Crab detection

The offset in the Crab pointing was expected to broaden the peak at 170 keV to 8 keV FWHM. As a consequence of the uncertainty of the focal spot position, we made 30 data-analysis trials in the mechanically possible range. The maximum significance during this "fishing expedition" was found by assuming offsets of +5 mm in the vertical and +10 mm in the horizontal directions. With this detector offset and event discrimination the useful exposure time is reduced to 72 min, yet the spectrum (Fig. 2(b)) shows an excess of about 33 photons at 170 keV, a 3.5σ effect corresponding to a probability of 99.976%). For comparison, a spectrum of all single events for every detector at float altitude (reference for background) is shown in Fig. 2(a).

To obtain the actual significance of the detection, the number of trials has to be taken into account. The trial positions are strongly dependent since spectra from adjacent positions (1 mm apart) contain a large number of common events. A series of flight simulations using background noise only (no Crab signal) showed that our 30 trials are equivalent to about 4.2 independent trials – the actual significance of our detection is hence 3σ ($0.99976^{4.2} \approx 0.99898$).

3.5. Flight performance

For an off-axis source, the diffraction peak is broadened (i.e. 8 keV) but its integral remains roughly constant. Assuming a Crab flux of $(1.42 \pm 0.02) \times 10^{-4}$ photons s^{-1} cm^{-2} keV^{-1} at 170 keV (Bartlett, 1994), the detection of 33 photons corresponds to a peak efficiency of $\sim$12.5 $\pm$ 4% (i.e. 64 cm^2 effective area). The value is obtained using the following instrumental parameters: a mean detector efficiency of 45.5% (at 170 keV), a deadtime of 15%, a bandpass of 3 keV FWHM for the perfectly pointed lens (deduced from Eq. (3) and the detector resolution), and a mean atmospheric transmission of 67% (at 170 keV, altitude of 41 km).

3.6. Long distance test

To confirm the results of the flight, a 205 m long test range was set up at an aerodrome near Figueras on the Spanish Mediterranean coast. The X-ray source consisted of an industrial X-ray generator with a 2.5×2.5 mm tungsten target. The voltage and current were set to 250 kV and 1 mA, respectively, allowing for sufficient X-ray flux at 170 keV after absorption by 205 m of air. The peak efficiency at "quasi infinite" distance (205 m, diffracted energy 165 keV) was measured to be $9.7 \pm 0.5\%$. The test also validates the relationship between distance and diffracted energy close to the asymptote at 170 keV (Fig. 3).

3.7. Diffraction efficiency

CLAIRE's peak efficiency ($\approx$10%) is a mean over the 556 crystals of the lens. Data obtained during lens tuning indicate that the performance of individual crystals varies strongly from crystal to crystal. Firstly, each of the eight rings uses a different set of crystalline planes – the theoretical peak efficiencies ranging from 25% at best ([1 1 1] crystalline planes) down to roughly 10% ([3 3 3] crystalline planes). Secondly, even within the same ring, a wide spread (factors of 2–10) of the measured peak efficiencies showed that the quality of the actual CLAIRE crystals is extremely heterogeneous. Nevertheless, the tuning data prove that real crystals can be as good as the Darwin model for "ideally imperfect" mosaic crystals predicts: the best crystals on the inner rings of the lens have been measured with peak efficiencies above 20%. A thorough discussion of the CLAIRE project is given in Halloin (2004).

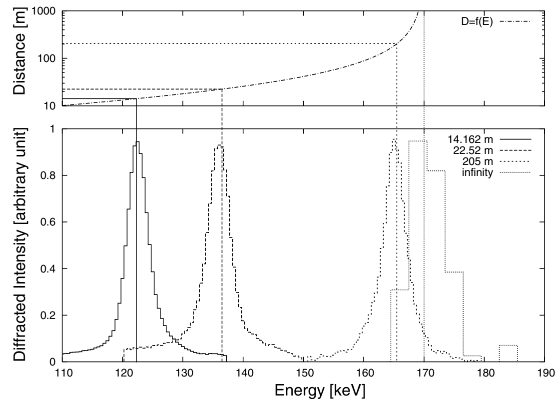

Fig. 3. Recorded spectra for various source distances (lower graph). The upper graph represents the distance of the source as a function of diffracted energy. The vertical lines show the theoretical corresponding energies. 14.162 m corresponds to the tuning distance ($E_{th} = 122.29$ keV). The measurement at 22.52 m ($E_{th} = 136.5$ keV) was also done in the laboratory with a partially tuned lens. 205 m is the distance of the generator on the long distance test range ($E_{th} = 165.5$ keV). The peak for an infinite distance is taken from the stratospheric flight (see above). Slight departures from the theoretical diffracted energy may be due to the shape of the incident spectrum or the calibration drift.

4. The MAX mission concept

Ultimately, the concept of a crystal diffraction telescope should be put to use in space where longer exposures and steady pointing will result in outstanding sensitivities. Based on the experience obtained with CLAIRE, we propose the mission concept of a space borne gamma-ray lens: MAX (von Ballmoos et al., in press). Featuring a Laue lens consisting of rings of Cu and Ge crystals, MAX simultaneously covers two wide energy bands of high astrophysical relevance: 810–900 keV for the observation of the ^{56}Ni decay chain in type Ia SN, 450–530 keV for the observation of e^-e^+ emission and the ^{7}Li line from novae. The lens has the shape of a ring (outer radius 111 cm, inner radius 86 cm) surrounding the lens spacecraft, its effective area amounts to 600 cm^2 both at 847 and at 511 keV. A small detector, maintained at a distance of 133 m by a second spacecraft flying in formation, collects the focused radiation.

4.1. Performance

The modeled narrow line sensitivity of MAX in each energy band is shown in Fig. 4. (Diffraction efficiency from the Darwin model/best CLAIRE crystals, specific background rate from SPI INTEGRAL; Jean et al. (2003).) Scaling the linear dimensions of MAX by a factor s will improve the sensitivity by a factor s^2. Fig. 4 also shows the

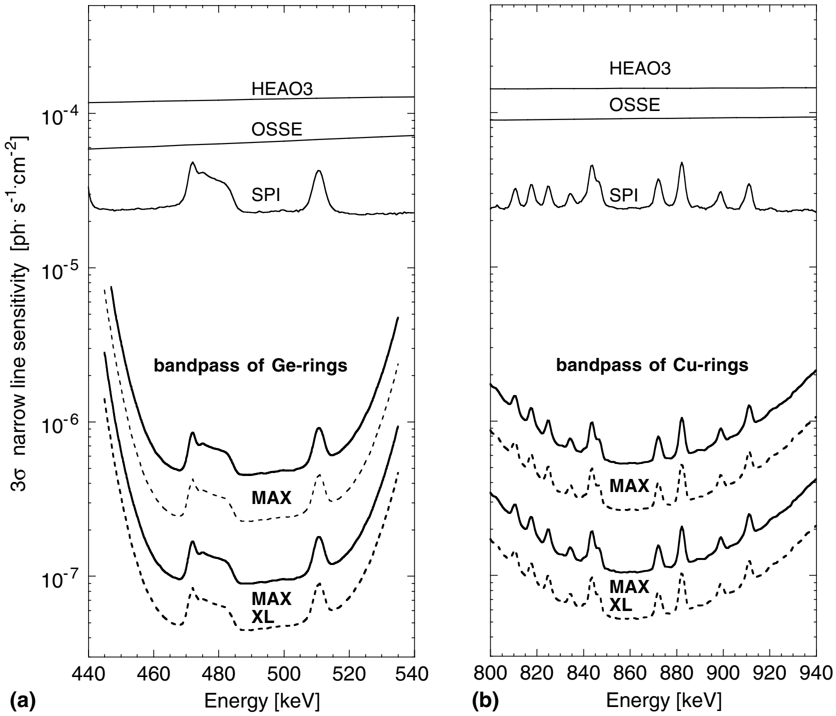

Fig. 4. 3 σ narrow line sensitivity of MAX and MAX XL compared with the achieved sensitivities of precedent missions (observing time 10^6 s). The performance is based on the measured detector background of SPI/INTEGRAL; the solid curves correspond to the diffraction efficiencies of mosaic crystals based on the Darwin model, the dashed curves indicate the potential of recently measured gradient crystals.

performance of a version for "MAX XL" – with an outer diameter of the ring-lens of 5 m (outer/inner radius of the ring lens: 250 cm/193 cm, focal length: 300 m).

4.2. Scientific objectives

The primary scientific objective of MAX is the study of type Ia supernovae by measuring intensities, shifts and shapes of their nuclear gamma-ray lines. When finally understood and calibrated, these profoundly radioactive events will be crucial in measuring the size, shape, and age of the Universe. Observing the radioactivities from a substantial sample of supernovae and novae will significantly improve our understanding of explosive nucleosynthesis. Moreover, the sensitive gamma-ray line spectroscopy performed with MAX is expected to clarify the nature of galactic microquasars (e^+e^- annihilation radiation from the jets), neutrons stars and pulsars, X-ray Binaries, AGN, solar flares and, last but not least, gamma-ray afterglow from gamma-burst counterparts.

5. Conclusion

During CLAIRE's stratospheric balloon flight in June 2001 an astrophysical source was observed with a γ-ray lens. Associated with the ground long distance test, these results validate the theoretical models and demonstrate the Laue lens as a powerful tool for nuclear astrophysics. The sensitive gamma-ray spectroscopy that can be performed by 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. Besides of high energy resolution ($E/\Delta E \approx 500$) and very good positioning, the mission concept MAX proposes narrow line sensitivities of few 10^{-6} to 10^{-7} photons s^{-1} cm^{-2}.

Acknowledgements

This work was supported by the US Department of Energy, Basic Energy Sciences, under contract no. W-31-109-Eng-38. The team at CESR acknowledges continuing support from the French Space Agency CNES.

References

Bartlett, L.M., 1994. High resolution gamma-ray spectroscopy of the Crab. PhD, University of Maryland.
Halloin, H., 2004. Premières lumières pour une lentille gamma", PhD, U. Paul Sabatier, Toulouse.
Halloin, H. et al., 2003. SPIE Proc. 4851, 895.
Halloin, H., et al., 2004. SPIE Proc. 5168, in press.
Jean, P. et al., 2003. A&A 411, L107.
Kohnle, A. et al., 1998. NIM A 416, 493.
Naya, J. et al., 1996. NIM A 373, 159.
von Ballmoos, P., et al., 2004. SPIE Proc. 5168, in press.