THE FIRST FLIGHT OF A GAMMA-RAY LENS

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ABSTRACT

On June 15, 2000, the first gamma-ray lens for astrophysics, CLAIRE, flew on a stratospheric balloon. The instrument features a Laue diffraction lens, a 3x3 array of cryogenic germanium detectors, and a balloon gondola stabilizing the lens to a few arcseconds. The lens consists of Ge-Si mosaic crystals, focusing gamma-ray photons from its 366 cm^2 area onto a small solid state detector, with only 18 cm^3 equivalent volume for background noise. The diffracted energy of 170 keV results in a focal length of 279 cm, yet the entire payload weighed under 500 kg. CLAIRE was launched by the French Space Agency CNES from its base at Gap-Tallard in the French Alps, and was recovered intact, after more than 6 hours at float altitude (3 mbar), in the department of the Landes in the Southwest of France. All of the systems appear to have behaved nominally during the flight.
The primary objective of this technological balloon flight was to test a gamma-ray lens under space conditions. Detailed analysis of the data will involve identifying which data were obtained when CLAIRE was pointing at our main target, the Crab nebula and how many photons focused by the lens were received.

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.
One possible way out of this impasse consists of taking advantage of the phase information of the photons. Gamma-rays can interact coherently inside a crystal lattice provided that angles of incidence are very small. The small scatter-angles and the high penetration power of gamma-rays made us choose Bragg-diffraction in Laue geometry, this is, the photons traverse the crystal using its entire volume for diffraction. As a consequence of focusing from a large collecting area onto a small detector, the background of a crystal diffraction telescope is extremely low, making possible unprecedented sensitivities.
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 arc seconds 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 keV to 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 gamma-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 redshifted annihilation lines from AGN s and

annihilation afterglow of gamma-ray burst counterparts, but also two-dimensional intensity mapping of strong continuum sources with unprecedented angular resolution.

After testing the principle of a gamma-ray lens (Naya et al. 1996) on the ground, measuring the diffraction efficiency of our Ge crystals (Kohnle et al. 1998a) and developing a very accurate (100 nm) feed-back loop to tune automatically each crystal (Kohnle et al. 1998b), CLAIRE is the next logical step towards a space borne crystal lens telescope. Its purpose is to demonstrate, for the first time, a gamma-ray lens for astrophysical observations.

THE PRINCIPLE OF A DIFFRACTION LENS

Our gamma-ray lens consists of a frame on which concentric rings of germanium-silicon single crystals are mounted (Fig. 1)

In order to be diffracted, an incoming gamma-ray must satisfy the Bragg-relation

$$2\, d \sin(\theta) = n\, \lambda \tag{1}$$

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.

Each ring uses crystals with the same crystal plane spacing (definite crystallographic orientation). 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:

$$R = D \tan 2\Theta \tag{2}$$

where D is the focal distance.

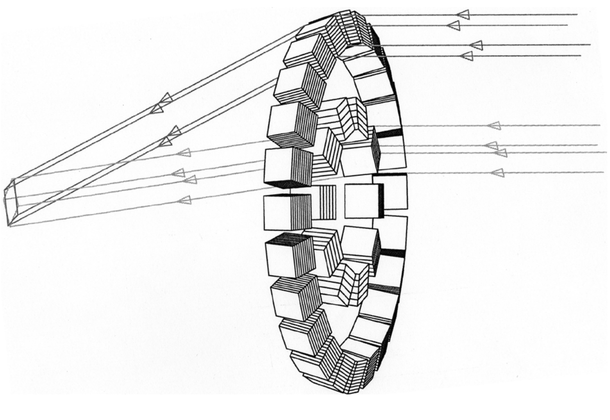

Fig. 1 The principle of the gamma-ray lens.

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 register a much larger signal than it would have intercepted if it was exposed to the radiation field directly.

While the observation of nuclear lines is *the* natural objective for a spaceborne gamma-ray lens, proving the principle on a balloon flight ironically implies observation of a continuum spectrum. This choice is imposed by two imperatives : 1) the characterization of a new instrument concept requires a well-studied source 2) the challenge of pointing a first balloon-borne lens makes a short focal length preferable, therefore excluding high energies for the lens tuning.

Since no gamma-ray line source in the range up to a few hundred keV has been surely established yet, an acceptable alternative was the continuum flux in a narrow energy band of the well-known Crab nebula and pulsar. The diffracted energy band was more or less arbitrarily chosen to be 170 keV for a source at infinity - the choice being motivated by the fact that 511 keV is the third harmonic, and that a compact 511 keV source might be accompanied by 170 keV backscatter radiation (see eg. Smith et al 1993).

Unfortunately, for the balloon configuration, the energy band of a gamma-ray lens is proportional to the square of the diffracted energy :

$$\Delta E \approx \frac{2d \cdot E^{2} \cdot \Delta\theta}{nhc} \tag{3}$$

here, $\Delta\theta$ is the *mosaic width* of the crystal, i.e. the angular range over which the crystals reflect monochromatic radiation. While the bandpass ΔE of our crystals ($\Delta\theta \sim 45$) is of the order of 35 keV at an energy of 847 keV, it is only ~ 1.3 keV at 170 keV. The diffracted flux from the Crab, although assured , is thus only of the order of $7.8 \cdot 10^{-3}$ photons per second, assuming a source flux of $f_C = 1.5 \cdot 10^{-4}$ ph $cm^{2} \cdot s^{1} \cdot keV^{-1}$, an effective lens area of $A_e \approx 67$ cm^2, and a mean atmospheric absorption $\tau = 0.6$.

THE CLAIRE TELESCOPE

For its maiden flight CLAIRE's diffraction lens consisted 366 Ge(1-x)Si(x)) crystals arranged in 6 rings. The footprint of the individual crystals (1 x 1 cm and 0.7 x 1 cm respectively) results in a focal spot 1.2 cm diameter.

Crystal tuning was performed on a 20 m long optical bench at CESR. An X-ray generator (U=150 kV, I=200-400 μA), 14 m in front of the lens, served as calibration source for the tuning. The continuum spectrum which reaches up to 150 keV facilitates tuning with respect to using a radioactive source : instead of a blind search for diffraction at the accurate crystal inclination, the diffracted peak shows up promptly in the range of the continuum spectrum and has only to be moved to the adequate energy by tuning the crystal.

The lens axis is materialized by the invariant pixel on the CCD camera mounted on a rotating optical telescope in the center of the gamma-ray lens. Even when refocusing of the optical telescope (cal. source -> infinity) becomes necessary or the CCD camera is to be changed, the lens axis remains unchanged within a precision better than ~ 5 arc seconds.

The choice of the tuning energy of 122 keV at 14 m object distance allowed us to monitor the crystal

Launch :	5:36 UT, June 15, 2000, Aerodr me de Gap-Tallard (Hautes-Alpes)
Instrument weight :	500 kg
Balloon :	Zodiac, 400 000 m^3
Float altitude :	† 3 hPa (40 km), attained at 8:04 UT
Targets :	Crab nebula, Sun - active regions 9033, 9041, 9042
Achieved primary pointing (gondola) :	† 15 arc minutes azimuth and elevation error; stability 7 arc minutes
Achieved fine pointing (lens) :	† 3 arcseconds elevation/cross-elevation error; stability°: † 2 arcseconds
Termination :	14:37 UT, landing SW of Casteljaloux (Landes)

tuning with a small ^{57}Co source. The number of diffracted ^{57}Co photons was measured before and after transferring of the lens to the launch site, showing that the lens did not suffer detuning during the 6 hour drive from CESR Toulouse to Gap-Tallard.

The focal spot of the gamma-ray lens is materialized by the circle produced by a small laser mounted on the rotating central telescope. During flight the spot may wander around on the Ge-detector matrix as the primary stabilization seeks its central position. The focal spot ideally is on the central detector of our 3x3 HPGe matrix (element size 1.5 x 1.5 x 4 cm). The surrounding detectors can be used either to enhance the detection efficiency of source photons having undergone a Compton scatter in the center detector, alternatively they may be used for background rejection.

The gamma-ray detector consists of a high-purity 3x3 germanium matrix 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 x 1.5 cm x 4 cm and an internal electrode hole of 4-mm diameter. Preamplifier electronics are located in a pressurized aluminum capsule directly behind the detector matrix. No active anticoincidence shielding was used on this flight to reduce the background, but the detector and frontend electronics were surrounded by a lightweight lead shield. The detector matrix is cooled by a liquid nitrogen dewar that has been pressurized for the flight. The lens module, detector package (3x3 Ge matrix, pressurized dewar and Birmingham electronics), and fine pointing system are integrated into a telescope structure made entirely from composite materials (Figure 2). Because of the upper limit to the total mass for a flight in France (500 kg), the CLAIRE gondola is mainly a pivot. The 3m telescope structure, consisting of 18 carbon fiber spars and 3 honeycomb platforms only weighed 100 kg. The structure has been designed, manufactured and tested by the University of Birmingham.

CLAIREs pointing system was developed by the balloon division of CNES, with the help of the Observatoire de Gen ve, Switzerland. Two (almost) independent systems stabilize and point a target close to the sun with a precision better than 5 arc seconds.
The primary pointing system stabilizes and points the entire telescope to within 10 arc minutes with the help of an azimuthal pivot (that also measures the torque between gondola and balloon), a zenithal actuator, and a system for passive damping of gondola resonances.
The fine pointing system consists of a gimbal that stabilizes and points the gamma-ray lens only. Fast commanding the gimbal is through two custom-made actuators, the pointing is controlled by gyros and inclinometers, offset corrections are measured by a sunsensor mounted on a sun-pointing platform, the absolute offset is calibrated and controlled by the central CCD camera. The pointing quality of the gamma-ray lens has been shown to be better than 3 arc seconds.

FIRST FLIGHT OF A GAMMA-RAY LENS

The Claire flight took place on Thursday June 15 - right in the middle of our launch window of only three days (June 14, 15 and 16). The payload weighted just a little less than 500 kg, the balloon was a 400'000 m^3 Zodiac. The launch was at 05:36 UT (07:36 local time) in conditions which were perfect. It went very smoothly using the auxiliary balloon technique routinely used by CNES.
Float altitude was reached in about 2.5 hours, just as the sun reached an angle where solar pointing became possible. The float altitude was less than 3 mbars, corresponding to 40 km. The temperature of the lens varied from 15 - 21 ¡C during the entire flight. The detector background was within 20% of our prediction (Laporte et al. 2000) - this is at a level of $1.3 \cdot 10^{-3}$ cts $cm^{3} \cdot s^{1} \cdot keV^{-1}$ at 170 keV. All 9 Germanium detectors showed nominal performance, line shifts were inferior to 0.4%, resolution at 170 keV was about 2 keV FWHM. The recorded events were tagged with respect to the internal clocks with 0.1 ms resolution.

The flight has shown that the required stability of the lens fine pointing is feasible (see table 1). The primary pointing system was able to keep the focal point on the detector for the majority of the time. Yet, as might have been expected with the first flight of such a complex system, optimizing and calibrating the pointing system took some time. Only detailed analysis will show how many source photons have been collected by the lens. Yet, knowing the time span of precise pointing and given the relatively high background in the unshielded detectors, we can say that the Crab is unlikely to have been detected significantly. Also, neither of the active solar regions

at which the telescope was pointed underwent an outburst during the ballonflight.
After a little more than 6 hours at float, the instrument landed softly in a cornfield close to Cateljaloux (Landes). The only sever damage was to some of the detector elements, while the lens seems to have survived the flight and recovery undamaged.

CONCLUSION

Our collaboration foresees a stepwise development of the balloon borne diffraction lens project. In June 2001, the upgraded CLAIRE telescope is scheduled for a further balloon flight. In order to reduce the time required for a positive detection, CLAIRE will be equipped with an active shield, reducing the detector background, also, the lens will be completely filled with diffracting crystals.
After consolidating the gamma-ray lens as a tool for nuclear astrophysics, successive balloon flights could use a lens tuned to higher energies - e.g. for the observation of the 511 keV annihilation line. This would require an instrument with a 3 times longer focal length. In such a configuration the instrument could help decide whether or not galactic micro-quasars are emitting a narrow e^+e^- annihilation line (von Ballmoos and Smither 1994).
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. A space borne crystal diffraction telescope will use a gamma-ray lens situated on a stabilized spacecraft, focusing gamma-rays onto a small array of germanium detectors on an extendible boom or on a small, freeflying spacecraft. A tunable crystal lens will permit the observation of any identified source at any selected line-energy in a range of 200 keV to 850 keV. Besides of an energy resolution of $E/\Delta E$~500 and very good positioning, such instruments will feature narrow line sensitivities ranging from a few 10^{-7} ph $s^{-1}cm^{-2}$ to 10^{-8} ph $s^{-1}cm^{-2}$ (MAX projects, Skinner and von Ballmoos 1999, von Ballmoos et al 2000). Since diffraction of a narrow energy band is ideally matched to the narrow lines in the domain of nuclear transitions, gamma-ray lenses clairly are vital to the future of nuclear astrophysics.

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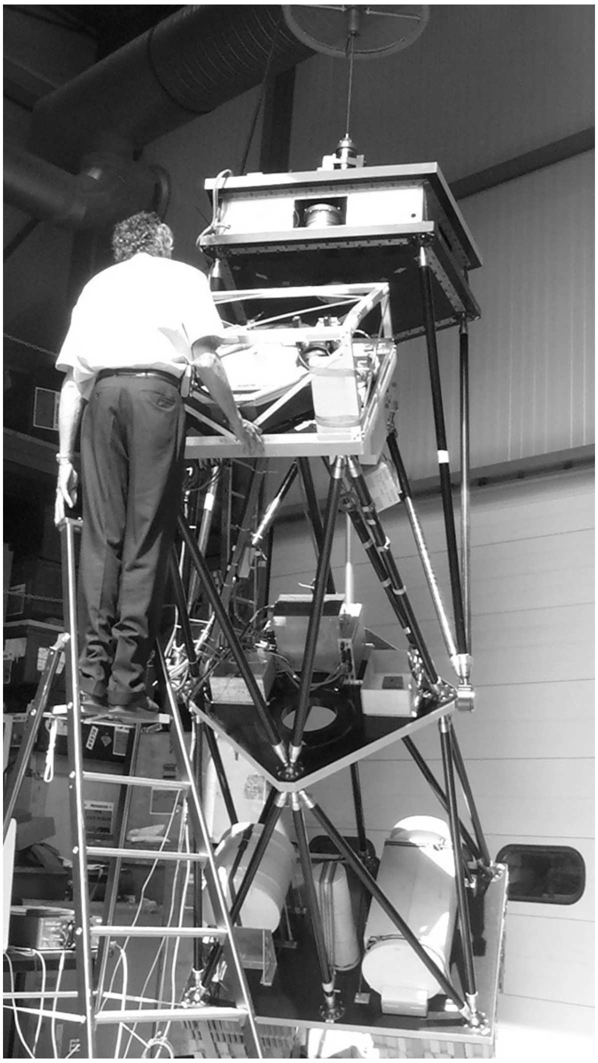

Fig 2 : The CLAIRE telescope during pointing tests at CESR Toulouse

For more information, publications and bibliography consult www.cesr.fr/~pvb/Claire .

Fig 3 : 15 June 2000, CNES balloon-base at Gap-Tallard : launch of the first telescope using a gamma-ray lens, CLAIRE

Crab signal (170 keV)
$f_C = 1.5 \cdot 10^{-4}$ ph $cm^2 \cdot s^1 \cdot keV^{-1}$

mean atmospheric absorption $\tau = 0.6$

effective lens area ($A_g = 335\ cm^2$, ε_{diff} ¯ 0.2)
A_e ¯ 67 cm^2

detection efficiency (singles, det 5) $\varepsilon_{det} = 0.6$

diffracted energy band (assuming a mean $\Delta\Theta$ ¯40) $\Delta E_{diff} = 1.3$ keV

detector background (170 keV)
$b = 1.3 \cdot 10^{-3}$ cts $cm^3 \cdot s^1 \cdot keV^{-1}$

detector volumeV = 9 cm^3

detector resolution $\Delta E_{det} = 3$ keV signal frequency

$\nu_s = f_C \cdot \tau \cdot A_e \cdot \varepsilon_{det} \cdot \Delta E \ \cdot T_{obs} \approx 4.7 \cdot 10^{-3}$ ph s^{-1}

noise frequency
$\nu_n = b \cdot V \cdot \Delta E_{det} \cdot T_{obs} \approx 3.5 \cdot 10^{-2}$ cts s^{-1}

=> 3.4 σ dans 5 h