TOWARDS THE FIRST LIGHT FOR A GAMMA-RAY LENS

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ABSTRACT The "gamma-ray lens" collaboration is presently preparing for a fundamentally new type of telescope, which is to be flown on a statospheric balloon by the French Space Agency CNES. The instrument features a Laue diffraction lens, a detector module with a 3x3 germanium array, and a balloon gondola stabilized to 15" pointing accuracy. The first flight is planned for the end of 1999 from Leon, Spain. The instrument's lens focuses gamma-ray photons from its 600 cm^2 area onto a small solid state detector, with only 18 cm^3 equivalent volume for background noise. Besides its excellent sensitivity, the telescope has outstanding angular and spectral resolution. The primary objective for its first balloon flight is to detect the Crab nebula measure extend at 170 keV with an unprecedented angular resolution of 78". For the first time in gamma-ray astronomy, the statistics will be dominated by the signal: for a residual atmosphere of 5.5 g/cm^2 and during a balloon flight at mid-latitudes, the observation of the Crab is expected to be essentially background free. The background will be only a few count/hour, with a detected source flux of 25 to 40 photons per hour at the Crab culmination. Scientific objectives for further flights include collapsed objects, SNRs, and broad class annihilators.

KEYWORDS: gamma-ray : instrumentation - gamma-ray : spectroscopy

1. INTRODUCTION

The purpose of CLAIRE is to demonstrate, for the first time, a gamma-ray lens for astrophysical observations. The CLAIRE telescope is composed of a crystal diffraction lens and a solid state detector matrix; carried by a fine pointing gondola, it is to be flown on a stratospheric balloon in fall winter 1999/2000. The development of a monochromatic 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 compulsory step to-

wards 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 30 arc seconds. Such a field-of-view will for the first time enable a mapping of the Crab nebula at low gamma-ray energies. During a balloon flight, the Crab is expected to be measured with a signal to noise ratio of 0.8 to 6.3, respectively for a passive and active shield. For the first time in this energy range, the detection statistics will be dominated by the source counts - this is a radical novum at gamma-ray energies where signal to noise 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. At a distance of 276 cm from the detector, the entire telescope is pointed with a precision of about 10 arcmin using conventional stabilization techniques of the gondola (magnetometers). Only the relatively light lens module ($\approx$ 30 kg) is pointed with high accuracy ($\approx$ 15 arcsec) by a star sensor.

2. THE TELESCOPE

Our gamma-ray lens is based on Laue diffraction [R. K. Smither et al., 1996] in Ge crystals. The diffraction angle is given by the Bragg relation (2dsin(θ)=nλ) where d corresponds to the separation between two consecutive crystalline planes. The Bragg angle (θ) corresponds to the crystal inclination in the lens frame and is less than one degree for gamma-ray energies. This angle depends on the wavelenght and makes the lens selective in energy. Combined with the radius (R) of the ring, the Bragg angle gives the focal lenght (F) of the lens : $\frac{1}{F} = \frac{2\theta}{R}$. By changing both the set of crystalline plane (d) and the Bragg angle to focuse the same wavelenght, it is possible to fill other rings having differents radii but keeping the focal lenght unchanged. The 576 Ge(Si) crystals are then arranged in 8 rings. At 2.76 meters is situated the HPGe matrix of 3x3 detectors. The size of the individual crystal (1 x 1 cm or 0.7 x 1 cm) gives a small focal spot ($\emptyset$ = 1.2 cm), smaller than the surface of one detector. Our goal is to place the focal spot on the central detector to use the others for background rejection.
Both the lens and the detector package (detector matrix, dewar and electronics) are fixed to the telescope structure. Because of our restrictive mass budget, the gondola is only a pivot. The telescope structure is attached to this pivot by the zenithal axis.

3. PERFORMANCE AND OBJECTIVES

3.1 The technical challenges

After testing the principle of a gamma-ray lens [Naya et al., 1994] on the ground and developing a very accurate feed-back loop to tune automatically each crystals [A. Kohnle et al., 1998], CLAIRE is the next logical step towards a space borne telescope using a tunable lens to observe at various energies. Yet, compared with laboratory tests, tuning a lens for a balloon flight is more demanding because of its narrow field of view (FOV) : the incident beam from an astrophysical source is parallel and a crystal misorientation of a few arc seconds decreases dramatically the diffraction efficiency. Because we have a lever of only 15 mm to move the Ge(Si) crystal, an arc second corresponds to a displacement of less than 100 nm. The feed-back loop developed by A. Kohnle et al. (1998) will be used for the crystal moving.

CRYSTAL LENS	
diffracting medium	576 1 cm^3 Ge(Si) crystals in 8 rings, 30 arc sec mosaic width
diameter of frame	45 cm
focal length	2.76 m
diameter of focal spot	1.1 cm FWHM for continuum radiation
field-of-view	78 arc sec for 170 keV
energy bandwidth (on-axis)	1.0 keV FWHM
effective collection area (170 keV)	113 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	$\approx$1.5 keV at 170 keV
total detector area	20.25 cm^2
efficiency at 170 keV	80%
POINTING REQUIREMENTS	
absolute pointing	optical axis of the lens $\leq$ 15 arc sec
telescope axis pointing	15 arc minutes
TELESCOPE SYSTEM	
energy range (on-axis)	170 ± 1.5 keV
effective background volume	18 cm^3 (focal spot in central pixel)
Signal counts on BG counts	6.3 with active shield (5h obs., Spain)

Table 1 : Characteristics and performance of the first telescope using a gamma-ray lens.

Another major challenge is to tune the lens on the ground for the observation of a source at an infinite distance. We cannot directly tune the lens for 170 keV, because this would imply placing a source at infinite distance. It is then impossible to verify the tuning before the launch using 170 keV photons. The way we have chosen to tune the lens is to place a continuum source (X-ray generator) at 14 meters from the lens. As with an optical lens, the focal plane comes closer to the lens with a source at a finite distance. With the distances used, a crystal will be correctly tuned if it diffracts an energy of about 122 keV (depending on the ring). We have already seen that an error of a few arc seconds in the crystal tuning decreases the diffraction efficiency. In term of energy a misorientation of 5 arc seconds represents a shift of 0.05 keV with respect to 122 keV. As the energy resolution of the detector is 2 keV, we need good statistics, with at least 10 000 photons. The intensity of our X-ray source combined with the crystal characteristics gives a number of photons impinging the detector of 5 to 20 per second, so we can estimate a time duration of 10 to 40 minutes to tune one crystal.

3.2 The astronomic target

For an astrophysical source, the number of detected photons depends on the crystals properties and the detector efficiency. Using the numerical values in the Table 1, we have simulated the total counts for a Crab observation during a 5h 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. For an active shield (30 mm of active BGO), the ratio of signal counts to background counts is larger than one, and equals 6.3. The observation of this well studied gamma-ray source will complete our knowledge on the telescope performance, in particular the diffraction efficiency of the whole lens.
The Crab nebula has an extend of 4 x 7 arc minutes in the visible domain. The nebular size seems to decrease with increasing photon energy. Two-dimensional maps of the Crab were obtained using a scanning modulation collimator in the 22-64 keV energy range [R.M. Pelling et al., 1987]. With a sufficient photon statistics, an instrument based on a gamma-ray lens, can constrain the extend of the Crab nebula at high energies. In fact if the telescope is pointed at the source, we expect 0.009 photons.s^{-1} for a nebula size of 20 arc seconds and 0.0075 photons.s^{-1} for 40 arc seconds.

4. CONCLUSION

The CLAIRE project is a high technological challenge: accuracies less than a micron are requiered 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 extend. Observation data of this balloon flight will be very helpful to calculate the performance of our instrument.

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