Gamma-Ray Lens Telescopes
for the Observation of Nuclear Transitions

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ABSTRACT. Gamma-ray lenses have become feasible today and present promising perspectives for future instrumentation. For the first time in high energy astronomy the signal/noise ratio will be dramatically improved as gamma-rays are collected on the large area of a lens from where they are focused onto a small detector. Besides an unprecedented sensitivity, such instruments feature very high angular and energy resolution.

1. The Potential of Crystal Diffraction Telescopes

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. 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): Gamma-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 (Smither 1989, von Ballmoos and Smither 1994, Naya et al. 1996, Kohnle et al. 1997):

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.

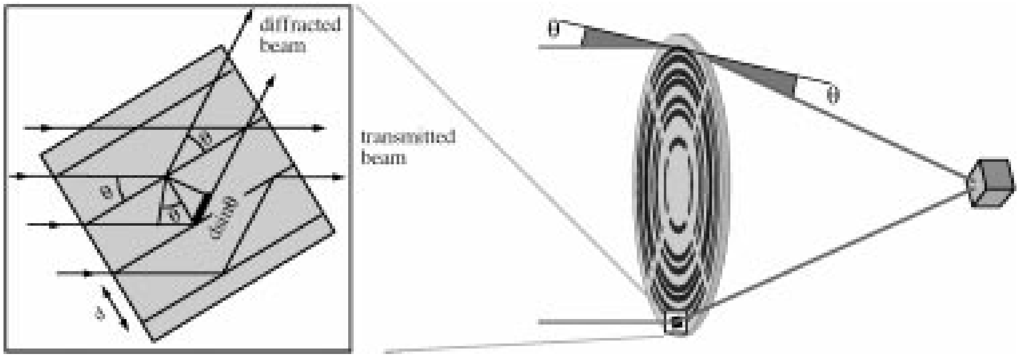

Fig. 1. The basic design of a focusing γ-ray telescope: The lens consists of quasi perfect single crystals arranged in concentric rings; γ-rays are focused into a common focal spot by Bragg-reflection in Laue geometry (θ is the Bragg angle, see eq. 1).

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 15-30 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 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 redshifted 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 and Prototype 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

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

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

TABLE I
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 ^{1})	(as Nova Musca, Nova Persei)
pulsars	$e^{-}e^{+}$ & NDL ^{1})	Crab, Vela ...
AGN	$e^{-}e^{+}$ & NDL ^{1})	NGC4151, 3C273 ...
solar flares	$e^{-}e^{+}$ & NDL^{1})	
γ-ray burst afterglow	$e^{-}e^{+}$ & NDL^{1})	gamma-ray burst counterparts

[1]) detection of $e^{-}e^{+}$ annihilation line and nuclear de-exitation lines (NDL) may be possible if an estimate of cosmolocical and/or gravitaional redshift is available

diffraction order, and 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 meassure a much larger signal than it would have intercepted if it was exposed to the radiation field directly.

A prototype lens telescope suitable for an astronomical instrument exists and has been tested in the laboratory at energies up to 700 keV (Naya et al. 1996). The system included a lens of 45 cm diameter consisting of 416 1 cm^3 Ge-crystals in 6 rings. In order to take maximum advantage of the particular properties of a focused γ-ray beam, a novel γ-ray detector consisting of a high-purity 3x3 germanium matrix (each of the 9 HPGe-detectors having a size 1.5x1.5x4 cm) housed in a single cylindrical aluminum cryostat is being used (Fig. 2). 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.

3. The balloon project

Together with our collaborators, from the Argonne Nat'l. Lab. (Chicago, USA), TESRE (Bologna, Italy), the CEA Saclay (France), the University of Birmingham (UK), the Observatoire de Geneve, and UNH (Durham NH, USA), we are presently preparing for the first flight of a balloon borne crystal diffraction telescope. The development of a monochromatic instrument offers its own outstanding scientific potential: Even during the relative short duration of a balloon flight, a variety of observational aims can be

Fig. 2. The γ-ray lens and the 3x3 Germanium matrix during the ground based system tests at ANL. When operating in the focal spot of the lens, the Ge detector is located 10-20 m behind the lens.

exploited: precise source localization, two-dimensional intensity mapping of sources with arc minute extent, the observation of narrow spectral lines. Furthermore, as a proof of principle, a balloon telescope is a compulsory 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 30 arc seconds. Such a field-of-view will for the first time enable a mapping of the Crab nebula at low γ-ray energies. During a balloon flight, the Crab is expected to be measured with a signal to noise ratio of 3 to 8. For the first time in this energy range, the detection statistics will be dominated by the source counts - this is a radical novum at γ-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 lens module is pointed with a precision of about 10 arcmin using conventional stabilization techniques of the gondola (magnetometers). Only the relatively light lens module ($\approx$20 kg) is pointed with high accuracy ($\sim$10 arcsec) by a star sensor. Successive flights will use a lens tuned to higher energies (line energies such as the 511 annihilation line) and have a field-of-view down to 15 arc seconds. In this configuration (longer focal length, narrower beam) the instrument could help decide whether or not the recently discovered galactic micro-quasars are emitting narrow e+e- annihilation lines.

4. Prototype of a tunable crystal diffraction lens

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. Yet, for a space instrument, the monochromatic limitation (due to the Bragg condition, eq.1) would be clearly a handicap. We are therefore developing a tunable gamma- lens

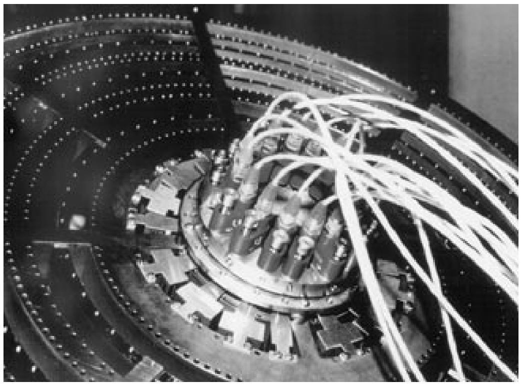

Fig. 3. prototype of a tunable γ-ray lens containing 16 picomotors and 16 eddy-current sensors in the [111] ring

which permits observation of any identified source at any selected line-energy of nuclear transitions. In order to tune the energy band of a crystal lens, two parameters have to be adjusted : the Bragg angle θ and the focal distance f. While f will have to be known to within a few cm, θ has to be adjusted with a precision of the order of arc seconds. Today, a protoype tunable lens has been realized in the laboratory and shown to function within the required specifications (Kohnle et al., 1997). The prototype contains 16 crystals in the [111] ring. Each one is tuned by using a picomotor to change the crystal inclination, and an eddy-current sensor to determine the momentary position. The picomotors use short pulses acting on a piezo crystal to turn a screw. In the sensors, an alternating voltage in the coil induces an eddy-current in a conductive plate at a distance d, which in turn acts on the primary B-field, thus changing the effective inductance L of the sensor coil. While the resolution of the sensors permits an angular resolution of 0.1 - 0.2 arcsec, the stepsize of the picomotors translates to 0.06 - 0.4 arcsec. The stability has been found to be better than 0.8 arcsec par day; the reproductibility of a certain tuning (precision after detuning) is better than 5 arcsec.

5. A Tunable Crystal Diffraction Telescope for Spaceborne Operation

A space borne crystal diffraction telescope will consist of a tunable lens situated on a stabilized spacecraft, focusing γ-rays onto a small array of germanium detectors perched on an extendible boom. While the weight of such an instrument is less than 500 kg, it can feature an angular resolution of ~15 arcsec, and an energy resolution of 2 keV over the range 200 - 1500 keV. The energy bandwidth is increasing from ~1 - 60 keV over this range. The sensitivity of such an instrument improves linearly with the surface of the lens and hence with the square of its maximal focal distance (see eq. 2). As an example, Fig. 4 presents the 3 σ narrow line sensitivity of a modest size lens with 90 cm diameter (its frame accommodates 700 germanium cubes in 11 rings) and a maximal boom length of 19 m. Today much larger orbital structures are achievable (the space station truss structure will have a length of more than 100 m); with a 60 m boom, a 2.9 m diameter lens has a sensitivity which is an order of magnitude better than the example in Fig. 4 - that is sensitivities of a few 10^{-8} γ's cm^{-2}s^{-1}!

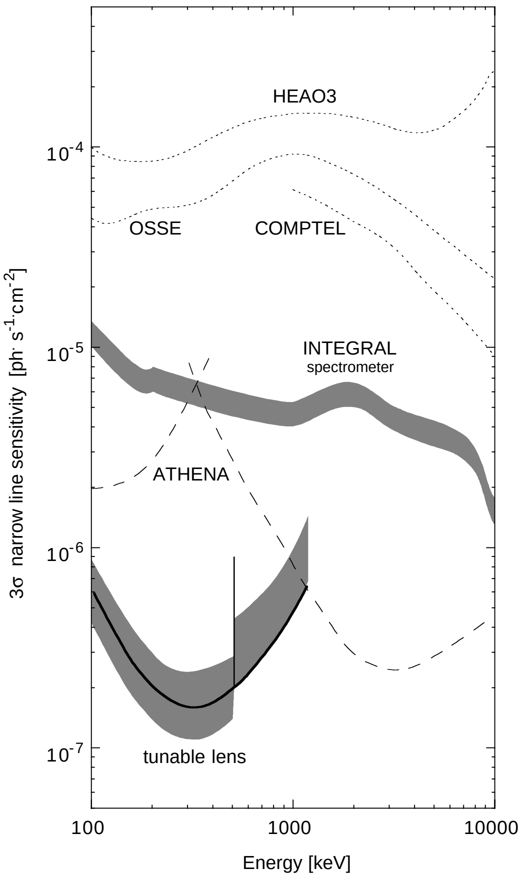

Fig. 4. The 3 σ narrow line sensitivity ($T_{obs} = 10^6$ sec) of a tunable crystal lens telescope compared with existing and future γ-ray spectrometers. A tunable lens can observe one line energy at the time; for a boom shorter than 20 m the sensitivity and its uncertainty is shown by the hatched area. If longer focal lengths can be achieved (i.e. 40 m), the sensitivity is improved at higher energies (solid curve) .

6. Conclusion

Even though technically innovative, a tunable crystal diffraction telescope for nuclear astrophysics has become feasible today : a) a crystal lens suitable for an astronomical instrument exists and has been tested in the laboratory; b) a prototype tunable lens equiped with miniature closed-loop regulators using piezo driven motors in conjunction with eddy-current sensors has been realized and succesfully tested, c) a monochromatic lens-detector system will be flown on a stratospheric balloon by the French Space Agency (CNES), before this decade is out ...

References

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