A TUNABLE CRYSTAL DIFFRACTION TELESCOPE FOR THE INTERNATIONAL SPACE STATION

P. von Ballmoos, A. Kohnle, J.F Olive, G. Vedrenne
Centre d'Etude Spatiale des Rayonnements, 9, av. du Colonel-Roche, 31400 Toulouse, France

R. K. Smither, P.B. Fernandez, T. Graber
Advanced Photon Source, ANL, 9700 South Cass Ave., Argonne Ill, USA

ABSTRACT

Even though technically innovative, a tunable crystal diffraction telescope for use in nuclear astrophysics has become feasible today. The focusing gamma-ray telescope we intend to propose for the space station consists of a tunable crystal diffraction lens, focusing gamma-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 features an angular resolution of 15”, an energy resolution of 2 keV and a 3 σ sensitivity of a few times 10^{-7} photons$\cdot$s$^{-1}\cdot$cm^{-2} (10^{6} sec observation) for any individual narrow line at energies between 200 - 1300 keV.

This experience would greatly profit from the continuous presence of man on the station. Besides of the infrastructure for maintenance and servicing of the various innovative techniques used for the first time in space, the available extra-vehicular robotics will facilitate deployment of the required boom structure.

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.

The telescope we intend to present for the International Space Station will, for the first time, use a gamma-ray lens. 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. As a result, this instrument can overcome the mass-sensitivity impasse and reach outstanding performances.

Until recently, focusing of gamma-radiation was regarded as an impracticable task. Today, gamma-ray lenses exist (Figure 1) and have been tested in the laboratory at energies up to 700 keV (Smither 1989, von Ballmoos and Smither 1994, Naya et al. 1996). Besides an unprecedented sensitivity, such an instrument features very high angular and energy resolution.

Fig. 1 The prototype gamma-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 was located 10-20 m behind the lens.

SCIENTIFIC POTENTIAL

The characteristics of crystal diffraction telescopes 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...

The concept of diffracting a narrow energy band is ideally matched to the observation of the narrow lines in the domain of nuclear transitions.

Besides the supernovae 1987A (Matz et al 1988) and 1991T (Morris et al 1995) the evidence for point like sources of narrow gamma-ray line emission has been mostly implicit at this point. Yet, various objects like galactic novae and extragalactic supernovae are predicted to emit detectable gamma-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 kind of sources match with the anticipated performance of a crystal diffraction telescope (Figure 2).

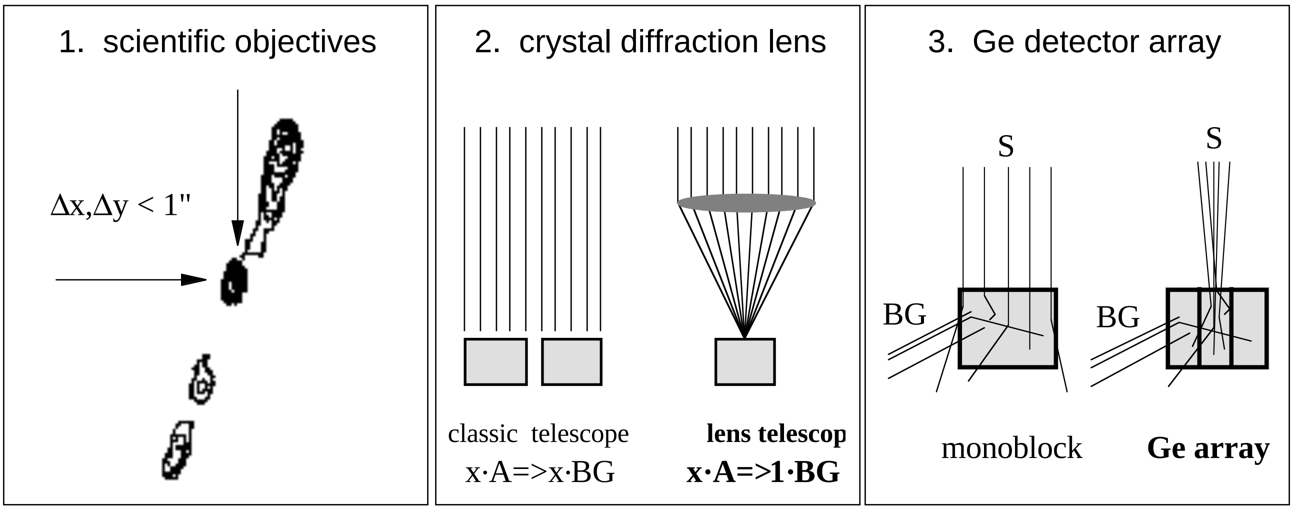

Fig. 2 : The premises of a focusing gamma-ray telescope : 1) due to the achievements of GRO and SIGMA scientific objectives are identified with position uncertainties less than 1”. 2) a first crystal diffraction lens exists at ANL and has been tested : sensitivity improvements with a large collector and a small detector are practicable. Angular resolution better than a minute and up to a few arc seconds are achievable. 3) a germanium detector array allows to take maximum advantage of a focused gamma-ray beam (source localization, further background reduction).

broad class annihilators: The recent discovery of broad annihilation features in several compact sources has shown that there is one or several types of objects that obviously can produce intense eruptions of positrons. The question is now whether these “broad class annihilators” also contribute to the positrons that produce the narrow 511 keV line which has been detected in the inner Galaxy by various spectrometers.

The galactic center source 1E1740-29 has been observed by the SIGMA telescope (Bouchet et al 1991) to emit a strong spectral features in the energy interval 300-700 keV that emanated and vanished within days. Radio observations of this object (see Fig. 2) reveal the presence of an AGN like structure with double sided radio jets emanating from a compact and variable core. If the “broad class annihilator” indeed is associated with the radio source, the origin of its high energy emission becomes a key question for gamma-ray astronomy.

Featuring a sensitivity of $\sim 10^{-6}$ ph·cm^{-2}s^{-1} at 511 keV and an angular resolution of 15”, a spaceborne crystal diffraction telescope can test hypotheses on the intensity and site of the narrow 511 keV line. If the radio lobes really track twin jets of positrons out to their annihilation sites in the superposed molecular cloud, a space borne telescope could localize the annihilation regions within less than a day: the predicted flux (Ramaty et al. 1992) of 10^{-4} ph·cm^{-2}s^{-1} (‘conservative number’) from the outer lobes of the jets would result in 5 σ detections in a few hours.

Novae : The detection of nuclear gamma-radiation from classical novae can offer unique insights into the conditions within the burning regions and the dynamic processes initiated by the runaway explosion (Leising and Clayton 1987). The high temperatures during the thermonuclear processes induce proton captures on most nuclei in the burning region, transforming stable seed nuclei into unstable proton rich nuclei. The extreme temperature gradient across the envelope at the peak of the burning produces rapid convective energy transport which can mix the envelope material. Large numbers of unstable nuclei with lifetimes longer than the convective time scale could appear at the surface where they are in principle detectable from their nuclear decay or positron annihilation gamma rays (the 1275 keV line from the ^{22}Na → ^{22}Ne decay, ß$^{+}$ decays of ^{13}N, ^{14}O, ^{15}O,^{18}F, and the 478 keV line from ^{7}Be → ^{7}Li). Unstable nuclei with even longer lifetimes (greater than a few days) could survive the ejection and thinning of the envelope. Then their decay could be observed in gamma rays even if their yields are relatively small.

Since the frequency of Nova explosions in our galaxy is about 40 per year, this kind of object is a very attractive candidate for point source gamma ray line observations.

A few hours after the explosion the emitted lines will be blue shifted ($\Delta E \approx 0.7\%$) as the observer would see only the emission from the approaching ejecta ($v \approx 2000$ km/sec) due to the optically thick medium (Harris et al 1991). This is relevant for the profile of the 511 keV line that is produced mainly during the first day of the explosion. The evolution in time over the first two hours is dominated by the positron annihilation produced by the ^{13}N decay while the ^{18}F decay dominates later.

After the first few days from the explosion the emitting material will become optically thin to the gamma rays so blue- and red shifted material will contribute to the observed flux, in which case a broadening ($\Delta E \approx 1.3$ %), but not a net shift of the line is expected.

Novae are possibly significant contributors to the Galactic ^{7}Li abundance - this has important cosmological consequences. The standard model requires that the primordial ^{7}Li abundance must be enhanced by subsequent nuclear nucleosynthesis, while the non-standard models require primordial ^{7}Li to be destroyed by some mechanism in population II dwarfs. The problem could be clarified if a stellar source of ^{7}Be was identifiable.

supernovae : Deeper insight in the explosive nucleosynthesis using the usual key isotopic decay chains identified for supernovae might be used to constrain the models (at this time, detonation or deflagration) and to understand the dynamics of the explosion through the shape and red (blue) shifts of the gamma-ray lines.

The expected fluxes are highly dependent on the models of the different types of SN explosions (especially the convection processes which could remove synthesized materials from the high temperature burning regions). The study of the explosive nucleosynthesis represents a crucial input to better understand the chemical history of the Galaxy. The nuclear gamma-ray lines from a supernovae that could be observed by a crystal lens are the 847 keV and 1238 keV line from the decay chain ^{56}Ni -> ^{56}Co -> ^{56}Fe, the 1156 keV line from ^{44}Ti, and the 1173 keV line from ^{60}Fe. The photons produced by the nuclei in the shell have noticeable Doppler-shifts due to the motion of the expanding supernova ejecta (a few 10000 km/s).

A large broadening of the lines - up to 40 keV at 847 keV is expected for SN type I where the shell gets transparent relatively early. At this energy the bandwidth of a crystal diffraction telescope is about 16 keV FWHM which corresponds to > 35% of the flux in the SN line. Tuning parts of the lens to different energy bands or scanning the line profile in energy will provide a complete coverage of these potentially broad features.

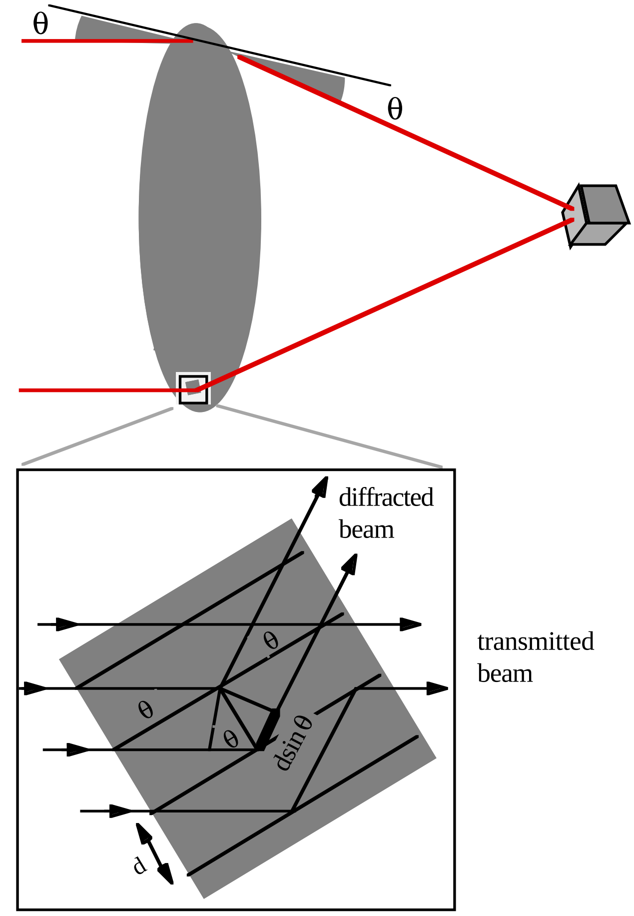

Fig. 3 The basic design of a focusing γ-ray telescope: The lens consists of quasi perfect single crystals arranged in concentric rings; γ-rays are focused into a common focal spot by Bragg-reflection in Laue geometry (θ is the Bragg angle, see eq. 1).

For supernovae of type II (core collapse SN - the gamma-ray flux is initially obstructed by the massive shell), the broadening is much less accentuated than for SNI's as the observations of SN1987A have shown. A volume of a few Mpc should be accessible to an instrument with a sensitivity of 10^{-7}-10^{-6} ph cm^{-2}·s^{-1} (T_{obs} 10^6 seconds) - this will make their detection possible for events occurring within our local cluster.

It has been suggested that the observability of SNIa can be expressed independently of the distance of the host galaxy since the optical peak magnitude of the SN should be directly correlated to the gamma-ray line flux (Arnett 1982). Indeed, the decay of the ejected gamma-ray isotopes *actually is* the energy source of the optical light curve.

Here, SN1991T has been used to establish a relation between gamma-ray flux f_{847} and optical peak magnitude m_V (the COMPTEL detection of SN1991T ^{6} gives $f_{847} \approx (5.3 \pm 2.0) \cdot 10^{-5}$ ph cm^{-2}·s^{-1} for an optical peak magnitude of $m_V = 11.6$)

$$\log(f_{847}/10^{-4}\ \mathrm{ph\ cm^{-2} \cdot s^{-1}}) \quad = \quad 0.4 \cdot (10.9 - m_V)$$

Thus a detectable flux of ~ 10^{-6} ph cm^{-2}·s^{-1} is expected from SNIa's with optical peak magnitudes $m_V < 16$. In recent years (2/1987-6/1996), events of this magnitude and brighter were observed at a rate of about three per year (Tsvetkov et al. 1996).

THE PRINCIPLE OF A DIFFRACTION LENS

Our gamma-ray lens consists of a frame on which concentric rings of germanium single crystals are mounted (Fig. 3).

In order to get diffracted, an incoming γ-ray must satisfy the Bragg-relation

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

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

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

In order to take maximum advantage of the particular properties of a focused gamma-ray beam, a novel gamma-ray detector, consisting of a high-purity 5x3 germanium matrix housed in a single cylindrical aluminum cryostat will be used. 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 test included a lens of 45 cm diameter consisting of 416 1 cm^3 Ge-crystals in 6 rings together with a 3x3-matrix of cooled HPGe-detectors each of size 1.5x1.5x4 cm (Fig. 1).

TOWARDS A TUNABLE DIFFRACTION LENS

The Bragg condition (eq.1) indicates that a gamma-ray lens is monochromatic. Since the crystals of the laboratory prototype are adjusted manually, changing the wavelength demands a considerable amount of work. For a space instrument, this limitation would be clearly a handicap. We are therefore developing a tunable gamma lens which permits observation of any identified source at any selected line-energy in a range of typically 200 keV to 1300 keV.

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 the focal 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. Adjusting the lens to an energy $E=E_{ref}+\Delta E$ requires that each of the single crystal is rocked by an angle $\Delta\Theta$ with respect to the position of a reference energy E_{ref} (i.e. 511 keV) in order to satisfy the Bragg condition anew (Figure 4).

For a lever of ~ 3 cm, the change of the distance z has to occur with a precision better than the rocking curve for a single crystal. i.e. < 0.25 µm. The dynamic range required for tuning the [111] crystals from 200 keV to 1300 keV is 0.25 mm (0.5°), for the [440] crystals.

First tests of a tunable prototype are currently in progress with a lens equipped with 28 crystals in the innermost ring using a system of picomotors and eddy-current sensors to change the crystal inclination and determine the momentary position. The picomotors use short pulses acting on a piezo crystal to turn a screw, the distance change per pulse being 15-20 nm. The current position is determined using eddy-current sensors, with a coil being in the sensor head. 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. The resolution of the sensors is 30 nm over a dynamic range of 0.5 mm, sensors with 1 mm range and similar resolution are available.

The instrument we intend to propose for the Space Station could consist in a tunable crystal diffraction lens, focusing gamma-rays onto a small solid state detector perched on an extendible boom. The lens consists of a frame less than one meter in diameter, accommodating 700 tunable germanium crystals in 11 concentric rings. While the lens pointing has to be assured to within a few arc sec, the position of the detector will have to be stabilized to a few cm's only. A small array of Ge-detectors, surrounded by an anticoincidence shield, will receive the gamma-ray beam at the focal spot which lies at a distance of 6 to 20 m (or up to 40 m) behind the lens.

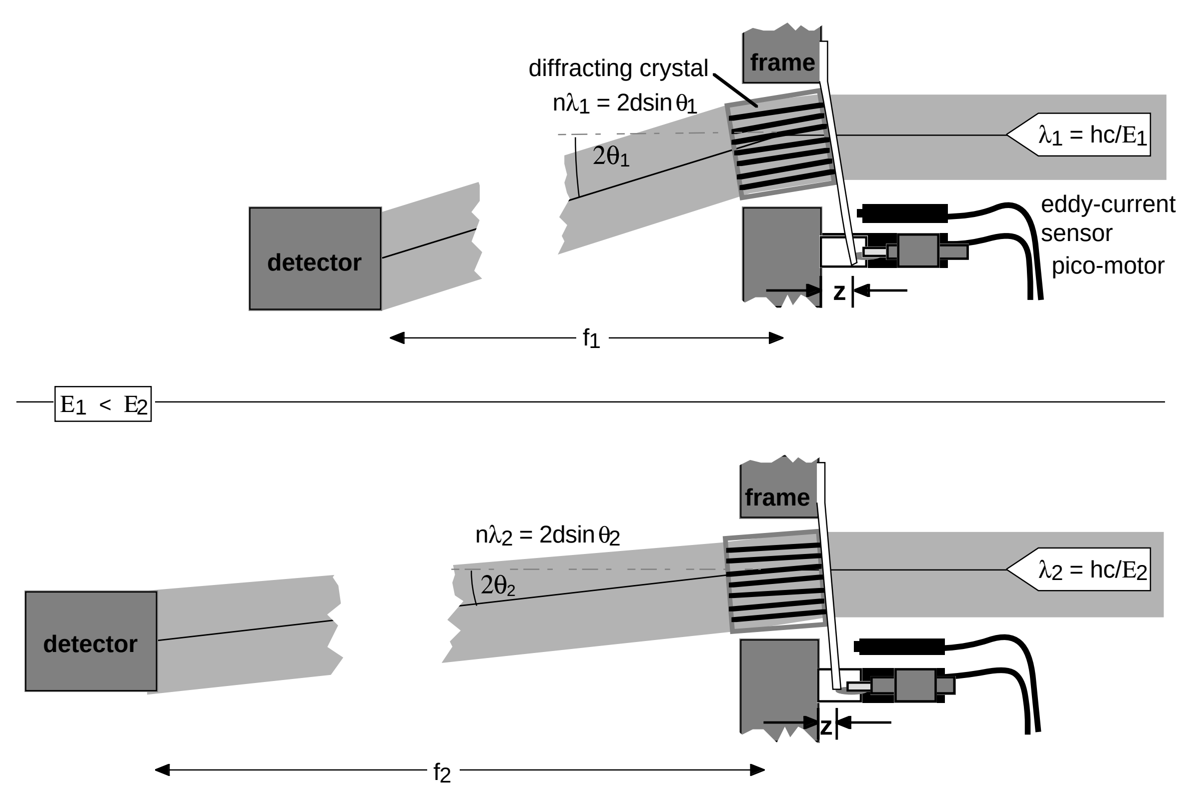

Figure 4 : the principle of lens tuning : in order to tune the energy band of a crystal lens, two parameters have to be adjusted : the Bragg angle Θ and the focal distance f. For a given energy, the diffraction angle θ of a crystal is adjusted by a closed loop system consisting of a piezo-driven actuator that varies the distance z and an eddy-current sensors controlling the displacement.

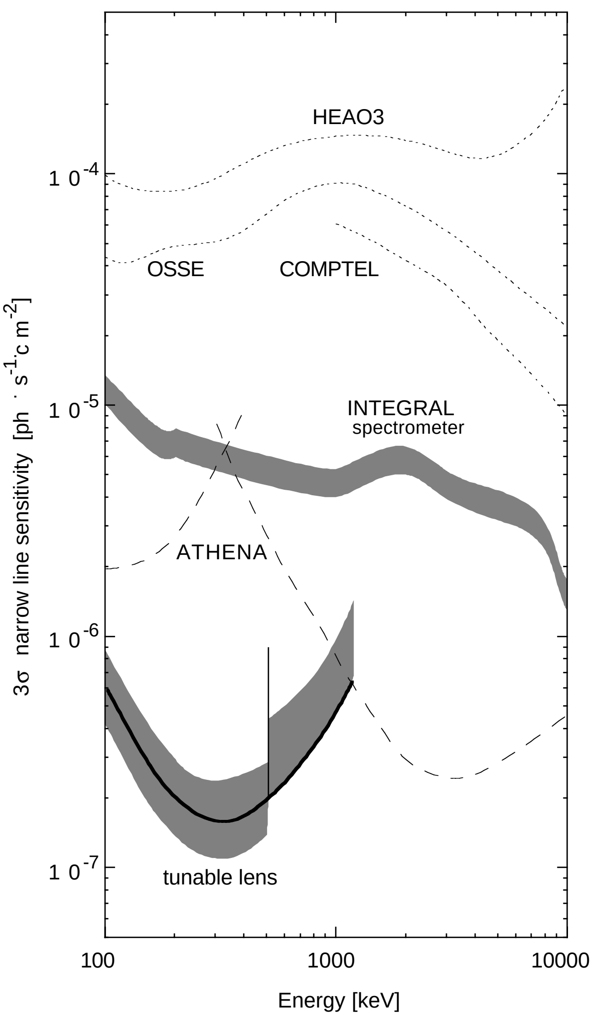

Fig. 5: The 3 σ narrow line sensitivity ($T_{obs}=10^6$ sec) of a tunable crystal lens telescope compared with existing and future γ-ray spectrometers. A tunable lens can observe one line energy at the time; for a boom shorter than 20 m the sensitivity and its uncertainty is shown by the hatched area. If longer focal lengths can be achieved (i.e. 40 m), the sensitivity is improved at higher energies (solid curve) .

CONCLUSION

A tunable crystal diffraction telescope for nuclear astrophysics has become feasible today: 1) A monochromatic prototype lens suitable for an astronomical instrument exists and has been tested in the laboratory at energies up to 700 keV. 2) The energy-tuning of single crystals is possible using today's piezo-technology; a first tunable lens including 20 closed-loop system is presently being tested. 3) Germanium detector arrays are manufactured today and have demonstrated their advantages in conjunction with the prototype lens. 4) Various space experiments have been carried out using extendible booms.

The weight of such an instrument is less than 500 kg, yet it features an angular resolution of 15", an energy resolution of 2 keV and a 3 σ narrow line sensitivity of a few times 10^{-7} photons s^{-1} cm^{-2} (10^6 sec observation) at energies between 200 - 1300 keV. (Fig. 5). The energy bandwidth will be of 1-50 keV over this range (increasing with energy).

The concept of diffracting a narrow energy band is ideally matched to the narrow lines in the domain of nuclear transitions. 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 in fact a natural target for such an instrument : The nuclear lines of extragalactic supernovae (^{56}Ni , ^{44}Ti, ^{60}Fe) and galactic novae (p^-p^+ 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 but also two-dimensional intensity mapping of strong continuum sources with unprecedented angular resolution.

Because of the various innovative techniques used for the first time in space this experience would greatly profit from the continuous presence of man. While the station's infrastructure will enable maintenance and servicing of the lens-nanotechnology and cryogenic Ge-detector arrays, the extra-vehicular robotics available on the station will facilitate deployment of the required boom structure. The ATV is a natural choice to carry out the transfer to/from a closeby orbit where observations with the gamma-ray lens will be made.

As an R&D project, the tunable gamma-ray lens project is supported by the French Space Agency CNES since 1994. Also, our Laue Crystal Telescope (LCT) is under study as a part of the Hard X-Ray Telescope (HXT) which has been selected by NASA for a mission concept study in 1995 (NRA 94-OSS-15, CoI's LCT : B. Smither, P. von Ballmoos).

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A solution to the sensitivity problem consists in seperating the detecting volume from the collecting surface (as at lower photon energies) in order to *concentrate* photons from a collector onto the detector.