A SPACE BOURNE CRYSTAL DIFFRACTION TELESCOPE FOR THE ENERGY RANGE OF NUCLEAR TRANSITIONS

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Abstract. Recent experimental work of the Toulouse-Argonne collaboration has opened the perspective of a focusing gamma-ray telescope operating in the energy range of nuclear transitions, featuring unprecedented sensitivity, angular and energy resolution. The instrument consists of a tunable crystal diffraction lens situated on a stabilized spacecraft, 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 narrow line sensitivity of a few times 10^{-7} photons s^{-1} cm^{-2} (10^6 sec observation). This instrumental concept permits observation of any identified source at any selected line-energy in a range of typically 200 keV to 1300 keV. The resulting "sequential" operation mode makes sites of explosive nucleosynthesis natural scientific objectives for such a telescope : 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, due to the erratic appearance and the sequence of half-lifes of these events. Other scientific objectives include the narrow 511 keV line from galactic broad class annihilators (such as 1E1740-29, nova musca) and possible redshifted annihilation lines from AGN's.

1. Introduction

Imaging combined with high resolution spectroscopy will be one of the major goals of the next generation of space borne gamma-ray telescopes. With the *spectrometer* on ESA's INTEGRAL mission, such an instrument will be available to the high energy community at the beginning of the next decade. High resolution spectroscopy will be performed by a bank of germanium detectors while the imaging is achieved by a coded aperture system [1]. The foremost objectives of this instrument will be the mapping of gamma-ray line sources emitting 10^{-4} photons s^{-1} cm^{-2} to a few times 10^{-6} photons s^{-1} cm^{-2}. Candidate sources of this intensity include the sites of recent nucleosynthesis, regions of e^+e^- annihilation and clouds where nuclear de-excitation by energetic particles takes place. Many of these potential sources will be galactic. Some of them might appear as extended structures - either because of their diffuse origin as the narrow 511 keV line [2], or because they are relatively closeby as the nucleosynthesis sites in the local spiral arm [3]. A wide field of view and a mid-scale angular resolution make the INTEGRAL spectrometer adequate for such objectives.
In the future, experimental gamma-ray astronomy has to find ways to improve the

observational performances. Yet, achieving sensitivities better than 10^{-6} photons s^{-1} cm^{-2} and resolutions better than fractions of a degree seems to be impossible with the presently practiced instrumental concepts: even larger collection areas are synonymous with larger detectors and thus again higher background noise.

A new type of gamma-ray telescope featuring a Laue-diffraction lens can overcome the impasse of present detectors where the collection area is identical to the detection area. This focusing gamma-ray telescope (VB&Smither, Smither at al) is designed to collect e^+e^- annihilation radiation on a large effective area (~ 150 cm^2) and focus the photons onto a Germanium detector matrix with a small equivalent volume for background noise (~14 cm^3). As a balloon-borne instrument it can provide high energy- and high angular resolution (2 keV, 15 arc sec, respectively) combined with an excellent sensitivity (~$3 \cdot 10^{-5}$ photons s^{-1} cm^{-2} @ 511 keV). The performances of this Ge-lens/Ge-matrix system have been verified in June/July 1994 during laboratory measurements with a ground based prototype [XX Naya 2]. The instrument has first been proposed as a balloon-borne telescope with the lens tuned to diffract 511 keV photons only. Such a configuration makes possible the study of galactic "microquasars" and other broad class annihilators in the light of e^+e^- annihilation during a balloon flight.

Ultimately however, the concept should be put to use in space where longer exposures and steady pointing would result in outstanding sensitivities. Yet, as a satellite instrument, a monochromatic lens would clearly be a handicap since its scientific objectives are too exclusive - already e.g. the possible annihilation line of most extragalactic sources (AGN's, quasars) would be inaccessible because of cosmological redshift.

Here we present a space borne crystal diffraction telescope using a tunable gamma-ray lens for the energy range relevant for nuclear transitions 200 keV - 1300 keV. An "adaptative gamma-ray optic" permits observation of any identified source at any selected line-energy in a range of typically 200 keV to 1300 keV. The "sequential" operation mode resulting from such a concept makes the sites of explosive nucleosynthesis natural targets for a tunable crystal diffraction telescope. This and other scientific objectives are discussed in the next section. The characteristics, feasibility and performance of a possible satellite diffraction telescope are described in section 3 and 4 respectively.

2. The scientific case for a tunable crystal diffraction telescope

According to our present view of celestial gamma-ray sources in the energy range of nuclear transitions, narrow lines seem to be generally emitted from extended distributions while broad lines tend to be radiated by point sources. Besides of the supernovae 1987A (XX) 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. We therefore have to ask a) where the scientific potential of a tunable diffraction telescope is and b) how many source candidates can be expected for such an instrument.

a) the scientific potential of a tunable diffraction telescope

Narrow line sources are though to have little angular extent if they are sufficiently distant or if the activity of their high energy processes is very recent. In either case the intensity of the emitted lines will be week as the relatively rare nucleosynthesis events like SN or novae are more likely to occur at large distance. A crystal diffraction telescope with its narrow beam and excellent sensitivity is optimally suited for the detection of such sources. Besides of the sites of explosive nucleosynthesis, the scientific objectives include : narrow 511 keV lines from galactic broad class annihilators (such as 1E1740-29, nova musca) and from AGN's; nuclear-desexcitation lines from energetic particle interaction with the ISM or dust grains (lines with energies above 1.3 MeV might become accessible to the lens if they are emitted by AGN's with high z); lines from the excited nuclei in solar flares (Murphy et al. 1990). In the following paragraphs some of the primary scientific objectives for a crystal diffraction telescope are outlined :

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 (Chen et al. 1993). The question is now whether these "broad class annihilators" also generate the positrons that produce the narrow 511 keV line.

The galactic center source 1E1740-29 has been observed by the SIGMA telescope to emit a strong spectral features in the energy interval 300-700 keV that emanated and vanished within days. Radio observations of this object 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 ~10^{-6} ph·cm^{-2}s^{-1} at 511 keV and an angular resolution of 15", the presented instrument 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, the telescope could localize the annihilation regions within less than a days: the predicted flux of 10^{-4} photons·cm^{-2}s^{-1} ("conservative" figure; Ramaty et al 1992) 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 (see Leising et al. 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. 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.

line energy &	width	mechanism	time scale	mass produced
478 keV	~ 6 keV	^{7}Be (EC)^{7}Li (10.4 %)	53.3 d	10^{-8} M_{o}

511-516 keV	~ 3 keV	ß+ decays of ^{13}N (862s), ^{14}O (102s), ^{15}O(176s),^{18}F(158m)	~ 1 day	XX
1275 keV	16 keV	^{22}Na (ß+)^{22m}Ne (90.4 %)	3.75 y	1.6 10^{-7} M_o

Table 1 : observable gamma-ray lines from novae

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. Line Profile : 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). This is relevant for the profile of the 511 keV line that is produced mainly during the first day of the explosion. The medium is still optically thick so that the observer would see only the blue shifted line (Harris, Leising, & Share, 1991). 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.

It has been pointed out that novae are possibly significant contributors to the Galactic ^7Li abundance (Arnould and Nørgaard, and Starrfield et al.) - this has important cosmological consequences. The standard model requires that the primordial ^7Li abundance must be enhanced by subsequent nuclear nucleosynthesis, while the non-standard models require primordial ^7Li to be destroyed by some mechanism in Population II dwarfs. The problem could be clarified if a stellar source of ^7Be 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 that 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 can remove or not 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 bandwith of a crystal diffraction telescope is about 10 keV FWHM which corresponds to 25% of the flux in the SN line.

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.

The observability of SNIa can be expressed independently of the distance of the host galaxy : The optical peak magnitude of the SN is directly correlated to the gamma-ray line flux - (the decay of the ejected gamma-ray isotopes *actually is* the energy source of the optical light curve). SN1991T has been used to establish a relation between gamma-ray flux f847 and optical peak magnitude m_V ($f_{847} \approx 2 \cdot 10^{-5}$ ph $cm^{-2} s^{-1}$, $m_V = 11.6$; Morris et al. 1995 XXX)

$$\log(f_{847}/10^{-4}\ \mathrm{ph\ cm^{-2}\ s^{-1}}) = 0.4 \cdot (9.8 - m_V) \qquad 1)$$

According to 1) an easily detectable flux of $> 2 \cdot 10^{-6}$ ph $cm^{-2} s^{-1}$ (taking into account 40 keV broadening) is expected from SNIa's with optical peak magnitudes $m_V < 14$. In recent years, events of this magnitude are observed about twice per year (Tsvetkov et al 1993)

b) How many source candidates for a crystal lens telescope ?

Because of its narrow beam (~15") and energy band (typically 8-15 keV) the observed "astronomical area" $\Delta l \Delta b \Delta E$ (gal. longitude interval, gal. latitude interval, energy interval) of a crystal diffraction telescope is very small : this implies that typically only one source and one gamma-ray line can be observed at any one time. Thus when comparing this type of instrument with a wide field-of-view telescope (as e.g. GRO COMPTEL, INTEGRAL) it may seem that the number of potential sources is inferior. In the following the number of sources is estimated for events of explosive nucleosynthesis : With the site ($\Delta l \Delta b$) of a nova or supernova known from its discovery (i.e. at optical wavelengths) and the sequence of escaping gamma-ray line energies (ΔE) given by nucleosynthesis theories, the pointing/tuning of the lens is obvious for any given time. The number of detectable sources then depends on the *depth* of space observed - the "astronomical *volume*" $\Delta l \Delta b \Delta E \Delta s$ - and thus on the *sensitivity*.

For galactic plane distributions the number of sources N_s should be roughly proportional to sensitivity^{-1} while for isotropic distributions the N_s even goes with the sensitivity$^{-3/2}$. With our sensitivities being two orders of magnitude lower (better) than the present experiments (that have sensitivities equal or close to the fluxes of SN, nova line fluxes), we can expect to observe a large number of this type of events during a mission.

When observing 511 keV from compact objects in the inner Galaxy (i.e. from a microquasar or from a nova explosion), the narrow field of the diffraction lens telescope ($\approx$ 15" at 511 keV) becomes an advantage : Whereas the bulge component of the galactic 511 keV emission (Purcell) is observed typically with a flux of 10^{-3} photons s^{-1} cm^{-2} by wide field-of-view instruments (an therefore prevails over the embedded point sources), a diffraction lens will only see a negligible fraction of the bulge flux while keeping its excellent sensitivity for point sources.

3. Characteristics and feasibility

A space borne telescope using an adaptative crystal diffraction lens will consist of three modules : the lens module, the detector module, and a boom. Optimally the lens module is located directly on the spacecraft, while the detector module is perched on the boom. The characteristics of a possible space borne gamma-ray lens telescope are summarized in Table 1 - an artists view of the concept is shown in Fig 1.

The *lens module* consists of a 90 cm diameter frame accommodating 700 germanium cubes. The single-crystal are organized in 11 rings, each ring uses a different set of crystalline planes to diffract the gamma rays. The crystals are oriented so that they all diffract the incident radiation of a certain energy to a same focal point. The 5 inner rings are composed of 1.5 cm thick crystals with an exposed area of 2 cm x 2 cm. Due to their thickness and position on the frame, these rings are optimized for the higher energies (a 1 MeV photon will still "see" ~$2 \cdot 10^5$XX [220] planes - spaced at a distance 160 times larger than its wavelength - while the probability of its absorption is only 36% XX). The crystals in the outer 6 rings each have the same geometric area (4 cm^2) as the inner ones, yet they are only 0.5 cm thick. These rings are optimized for the lower energies. Above 600 keV they still can be used for diffraction with higher order planes - however with reduced efficiency.
Tuning the lens to an energy $E=E_{ref}+\Delta E$ requires that each of the single crystal is rocked

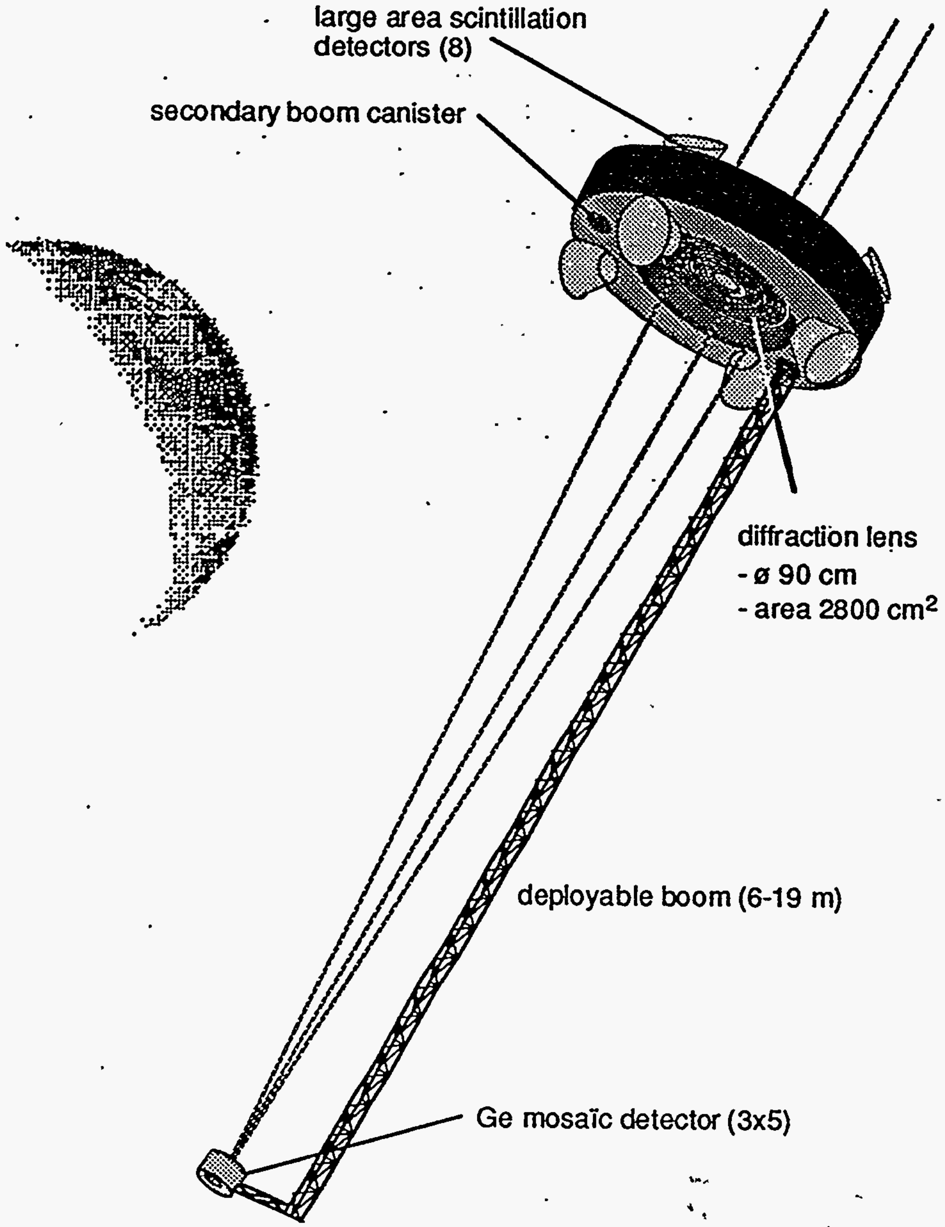

Figure 1 : “artists view” of a space borne crystal diffraction telescope. As a counterpart to the extremely directional lens telescope, a full sky monitor could complement the payload. This possibility is indicated by the eight large area scintillators that would use the Earth or the Moon as "rotating modulation collimator" in order to pinpoint transient sources of interest.

by an angle $\Delta\Theta$ with respect to the position of a reference energy E_{ref} (ie. 511 keV) in order to satisfy the Bragg condition anew.

$$\Delta\Theta = \arcsin(hc/2d(E_{ref}+\Delta E)) - \arcsin(hc/2dE_{ref})$$
XX2)

When tuning the crystal with the [220] planes for example from 200 keV to 1300 keV implies a $\Delta\Theta$ of 0.75 deg corresponding to a displacement of 0.4 mm over a 3 cm lever of the crystal base plate. It is essential that precision/repeatability of this motion is of the order of <2 arc seconds - this is : better than the rocking curve for a single crystal.
These requirements comply with the performance of a device consisting of a piezo-driven actuator and an Eddy-current sensor that measures the displacement. The miniaturized closed loop system is being built and tested at CESR and ANL.
A cross-shaped pattern in the central part of the frame is an optional aperture that can be used as coded mask. Together with the 5×3 detector matrix, this "minimask" adds the function of a small coded aperture telescope. The 3×3 base pattern mask (Sembay & Gehrels 1990) has actually 5×5 elements of the size 3×3 cm.

detector module : In order to take maximum advantage of the particular properties of a focused gamma ray beam, a germanium matrix will be used for the detector module. During the tests with our ground based telescope (Naya et al 1995) a similar germanium matrix has been found to be ideally adapted to resolve the beam energetically and spatially. The matrix consists of 3x5 detector elements, each one with a geometric surface of 3x3 cm and a height of 7-8 cm. The use of isotopically enriched ^{70}Ge as detector material reduces the β^- background component in our energy range while the enhanced β^+ production only effects the background above 1.5 MeV. Further reduction of the internal $n\beta$ components will be possible using the 15 segments. A matrix also offers the possibility to monitor the remaining background simultaneously to the astrophysical observation. The low intensity of spacecraft induced background will allow us to use a detector shielded only by a very light anticoincidence shield.
In space, cooling of the detectors can be performed by a small sterling cryogenerator, by a small tank liquid of liquid nitrogen, or passively by a radiator.

retractable boom : Since the focal length of the lens is increasing with energy, a retractable boom (ie. the coilable tube mast of SENER, Aguirre et al. 1987) will be used to the vary the distance between the lens and the detector module. An energy of 200 keV and 1240 keV respectively corresponds to a change in focal length of 3 m to 20 m - for the 511 keV positron annihilation line the distance lens-detector is 8.3 m. Booms have been used in gamma-ray astronomy on Apollo 15 with a NaI detector and on Mars-Observer for the Ge detectors. In both cases, the extension was around 7 m. Deploying the detector on a boom instead of the diffraction lens has several striking advantages: The mechanical requirements on the mast rigidity are less severe since a Germanium detector array is small and lightweight and thus easy to handle on a boom; moreover, twists and bends of even up to a few cm's are tolerable, as the focal spot can wander around on the detector array without significant loss of sensitivity. On the other hand, the stringent requirements for the pointing of the lens (typically ~ 5") can be satisfied on board the pointed and stabilized spacecraft. Finally, moving the detector away from the spacecraft reduces the background by up to an order of magnitude (depending on the energy, see

section 4).
In order to have a mechanically redundant system, the spacecraft will feature two 'detector-boom systems'. If both detectors were to be operated at the same time, different energy-bands could be observed simultaneously, or, maximum sensitivity at one energy band can be achieved by combining the two collector-zones.

Crystal lens		
diffracting medium	:	700 Germanium crystals (2cm x 2cm x 0.5/1.5cm)
diameter of lens frame	:	90 cm
tunable energy range	:	200 keV - 1300 keV
focal length	:	6.5 m - 19 m
diameter of focal spot	:	2.8 cm FWHM
acceptance angle (FOV)	:	15" FWHM
energy bandwidth	:	6 keV FWHM @ 511, 10 keV FWHM @ 847 keV
diffraction efficiency	:	25% @ 511 keV, 11% @ 847 keV
effective collection area	:	2800 cm^2
Detector matrix		
detector type	:	15 high purity Germanium, coaxial, 3x3x8 cm
energy resolution	:	2 keV (@ 511 keV)
total detecting volume	:	1080 cm^3
total detector area	:	135 cm^2
efficiency at 511 keV	:	54% @ 511 keV, 44% @ 847 keV
Telescope system		
system effective area	:	370 cm^2 @ 511 keV, 275 cm^2 @ 847 keV
secondary E-range (mask)	:	30-200 keV
effective volume for BG	:	72 cm^3

Table 2: Summary of instrument characteristics

Figure 2 : comparison of the narrow line sensitivities of past, present and future space borne gamma-ray telescopes ($T_{obs}=10^6$ sec). The shaded area for the tunable lens delineates the range the different background models (f=0.5 and f=0.1 for the upper and lower limit). The solid line is for f=0.2 (see text).

4. System performance

The imaging capabilities of a crystal diffraction telescope are defined by its beamwidth which is identical to the field of view of the lens : for compact sources discrete pointings of the object will be an appropriate observation mode, while extended structures as for example the jets of galactic microquasars will be scanned with the narrow beam. The field of view depends on the angular width of the mosaic structure of the crystals.
The calculations presented here assume a mosaic structure width of 10" resulting in a $\Omega \approx 16$" FWHM for the field of view. If a larger field of view is desirable for certain objectives, the beam can be widened by "detuning" the crystals with the individual closed loop servo systems.
Spectroscopy (Doppler shifts and broadening) of the lines is possible within the

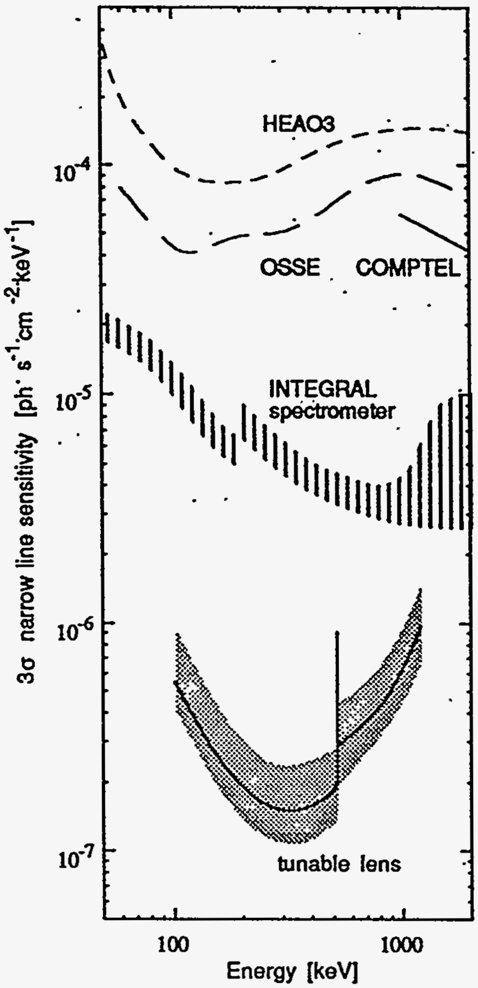

Figure 2 shows the estimated sensitivity of the presented instrument together with the sensitivities of past, present and future telescopes. For a crystal lens telescope, the point source sensitivity depends on the diffraction efficiency of the lens, the full energy peak efficiency and the background of the detector.

bandwidth of the crystals

$$\Delta E = E\frac{\Omega}{\Theta} \quad 3)$$

For the entire lens the bandwith is ~6 keV at 511 keV and ~15 keV at 1300 keV. The spectral resolution of present Ge detectors is typically 2 keV at 1 MeV.
For a point source at infinite distance we estimate diffraction efficiencies of the order of 26% at 200 keV, 8% at 1000 keV. The full energy peak efficiency of the detector matrix has been calculated by GEANT (80% at 200 keV, 39% at 1000 keV).

Here we use a background that is based on the *measured* ^{70}Ge spectrum of the GRIS experiment during a balloon flight at Alice Springs in 1992 (Barthelmy et al 1994). Yet, we assume that the ^{70}Ge background can be multiplied by a correction factor f<1 because of lower "shield leakage"- and "nβ"- contributions. The intensity of the background is decreasing when a detector is brought away from the "bright" spacecraft (or the earth). This solid angle effect has been demonstrated with a small szintillator that has been deployed on a boom on Apollo 15 (Trombka et al. 1973) : Compared to the on board spectrum, at a distance of 7m from the spacecraft the background in the range 0.2-1.3 MeV was down by a factor of 4-8, at 511 keV even by a factor of 10XX. For our instrument, we have assumed that the spacecraft induced background will be strongly reduced for the above reason. Furthermore, the resulting low mass (light shield) of the detector module will again reduce the background ($n\beta^-$ and $n\beta^+$ components, see Naya et al. 1995) as less neutrons are produced compared to the present heavily shielded gamma-ray spectrometers.

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