MAX - a gamma-ray lens for nuclear astrophysics

Peter von Ballmoos[a], Hubert Halloin[a], Gerry Skinner[a], Bob Smither[b], Jacques Paul[c], Nikolai Abrosimov[m], Jose Alvarez[d], Pierre Astier[l], Pierre Bastie[i], Didier Barret[a], Angela Bazzano[n], Arnaud Boutonnet[e], Pascal Brousse[e], Bertrand Cordier[c], Thierry Courvoisier[g], Guido DiCocco[h], Andrea Giuliani[j], Bernard Hamelin[k], Margarida Hernanz[d], Pierre Jean[a], Jordi Isern[d], Jürgen Knödlseder[a], Philippe Laurent[c], François Lebrun[c], Alexandre Marcowith[a], Vincent Martinot[e], Lorenzo Natalucci[n], Jean-Francois Olive[a], Reynald Pain[l], Rachida Sadat[f], Hervé Sainct[e], Pietro Ubertini[n], Gilbert Vedrenne[a]

[a]CESR, 9, av. du Colonel-Roche, 31028 Toulouse, France
[b]Argonne Natl. Lab, 9700 South Cass Avenue, Argonne, Il, 60439, USA
[c]Service d'Astrophysique, CEA- Saclay, 91191 Gif sur Yvette, France
[d]IEEC, Edif. Nexus, 08034 Barcelona, Spain
[e]Alcatel Space Industries, 26, av Champollion, 31037 Toulouse, France
[f]LA-OMP, 14, Avenue Edouard-Belin, 31400 Toulouse, France
[g]ISDC, Chemin d'Ecogia 16, 1290 Versoix, Switzerland
[h]TESRE, Via P. Gobetti, 10, 40129 Bologna,Italy
[i]Laboratoire de Spectrométrie Physique, BP 87, 38402 St Martin d'Hères, France
[j]Univ. Insurbia, Via Valleggio 11, Como, Italy
[k]Institut Laue-Langevin, BP 156, 38042 Grenoble, France
[l]LPNHE, 4, place Jussieu, Tour 33, 75252 Paris, France
[m]Institut für Kristallzüchtung, Max-Born-Str. 2, 12489 Berlin, Germany
[n]IAS, Via del Fosso del Cavaliere, 100, 00133 Roma, Italy

ABSTRACT

The mission concept MAX is a space borne crystal diffraction telescope, featuring a broad-band Laue lens optimized for the observation of compact sources in two wide energy bands of high astrophysical relevance. For the first time in this domain, gamma-rays will be focused from the large collecting area of a crystal diffraction lens onto a very small detector volume. As a consequence, the background noise is extremely low, making possible unprecedented sensitivities. The primary scientific objective of MAX is the study of type Ia supernovae by measuring intensities, shifts and shapes of their nuclear gamma-ray lines. When finally understood and calibrated, these profoundly radioactive events will be crucial in measuring the size, shape, and age of the Universe. Observing the radioactivities from a substantial sample of supernovae and novae will significantly improve our understanding of explosive nucleosynthesis. Moreover, the sensitive gamma-ray line spectroscopy performed with MAX is expected to clarify the nature of galactic microquasars (e^+e^- annihilation radiation from the jets), neutrons stars and pulsars, X-ray Binaries, AGN, solar flares and, last but not least, gamma-ray afterglow from gamma-burst counterparts.

Keywords : gamma-ray optics, instruments for nuclear astrophysics

1. INTRODUCTION

Present telescope concepts for nuclear astrophysics are based on inelastic interaction processes : they make use of geometrical optics (shadowcasting in modulating aperture systems) or quantum optics (kinetics of Compton scattering). In the class of instruments that are based on geometrical optics, INTEGRAL probably represents the pinnacle of what is possible using current technology. Advanced Compton telescopes are ideally suited for MeV astronomy : they have the potential of achieving sensitivities of an order of magnitude lower, providing angular resolutions of a fraction of a degree over a wide field of view.

While the present generation of instruments have attained the physical limits for a space borne mission, pushing the performance even further leads to several apparently unsolvable problems : Improving the sensitivity of an instrument can usually be obtained by a larger collection area - in the case of classical gamma-ray telescopes this is achieved by a larger detector surface. Yet, since the background noise is roughly proportional to the volume of a detector, a larger photon collection area is synonymous with higher instrumental background. For “classic” gamma-ray telescopes, the sensitivity is thus increasing at best as the square root of the detector surface. Today, nuclear astrophysics has come to a mass-sensitivity impasse where “bigger is not necessarily better”.

A possible way out of this dilemma 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 led us to choose Bragg-diffraction in Laue geometry, that is, the photons traverse the crystal using its entire volume for diffraction. The concept of MAX is radically different from traditional gamma-ray telescopes: γ-rays are focused from the large collecting area of a crystal diffraction lens onto a very small detector volume. As a consequence, the background noise is extremely low, making possible unprecedented sensitivities. MAX constitutes a breakthrough for the study of compact sources by combining narrow line sensitivities of a few 10^{-7} $\mathrm{ph \cdot s^{-1} \cdot cm^{-2}}$ with high energy resolution ($E/\Delta E \approx 500$) and very good positioning.

2. THE SCIENTIFIC CASE FOR A GAMMA-RAY LENS

Gamma-ray line astronomy is an extremely powerful tool for nuclear astrophysics. This has been demonstrated by observations of the 511 keV and 1.809 MeV gamma-ray lines, attributed to the annihilation of positrons with electrons, and the radioactive decay of ^{26}Al, respectively. However, one of the primary objectives of gamma-ray line astronomy, namely the study of gamma-ray lines in individual supernovae, has only been sparsely exploited so far. In fact, supernovae present the most prolific nucleosynthesis sources in the Universe. Despite this fact, almost no direct data on their nucleosynthetic activity is available, and our present knowledge is mainly based on theoretical calculations that are compared to the abundance pattern observed in stars or the interstellar medium.

Gamma-ray line astronomy can considerably improve our knowledge about nucleosynthesis processes by direct observations of freshly produced elements. In particular, radioactive isotopes that are co-produced in the nucleosynthesis process can act as tracers, carrying unique information about the physical conditions at the burning sites. Their observation can provide severe constraints for nucleosynthesis theory, placing calculations on more solid grounds. Additionally, radioactive isotopes are valuable chronometers, providing access to manifold timescales. They can serve as tracers of stellar and interstellar mixing processes, casting light on the extremely complex physics of stellar turbulence and interstellar recycling.

Radioactive isotopes are not only expected from supernova explosions. Nova explosions may provide important quantities of fresh isotopes that may eventually be observable by their gamma-ray emission. Potentially, novae could be significant sources of ^{7}Li, providing an possible explanation to the observed ^{7}Li overabundance in young stars with respect to older populations. This hypothesis can be verified by means of gamma-ray observations of the 478 keV line, arising from the radioactive decay of ^{7}Be. An alternative source of ^{7}Li may be black-hole X-ray novae, where ^{7}Be could be produced in the accretion disk. Also in this case, gamma-ray observations should place interesting constraints on this nucleosynthesis channel. Compact objects may also release significant numbers of positrons in the form of jets, leading to 511 keV gamma-ray line emission in the inevitable process of annihilation. The observation of this line in these so called microquasars can then provide valuable information about the jet propagation.

As a result of the recommendations made by the MAX Scientific Advisory Group, and following a workshop held during the “rencontres de Moriond” in March 2002, the mission concept for MAX [1] has been defined as follows :

MAX is to feature *simultaneous* focusing in two broad energy bands of high astrophysical relevance. As the primary scientific objective of MAX is the study of the ^{56}Ni → ^{56}Co → ^{56}Fe decay chain in type Ia supernovae, the principal energy band is centered on the 847 keV line from ^{56}Co. The second energy band of MAX is centered on 500 keV, with the objective of studying electron-positron annihilation emission (galactic microquasars, neutrons stars and pulsars, X-ray Binaries, AGN, solar flares and gamma-ray burst afterglow). The width of the energy band permits the observation of redshifted e+e- lines from compact objects (eg. the supermassive black hole in the center of our Galaxy), as well as the study of the 478 keV de-excitation line from ^{7}Li.

3. THE PRINCIPLES OF LAUE LENSES

In a crystal diffraction lens, crystals are disposed on concentric rings such that they will diffract the incident radiation of a same energy onto a common focal spot (Fig 1). In order to be diffracted, an incoming gamma-ray must satisfy the Bragg-relation

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

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

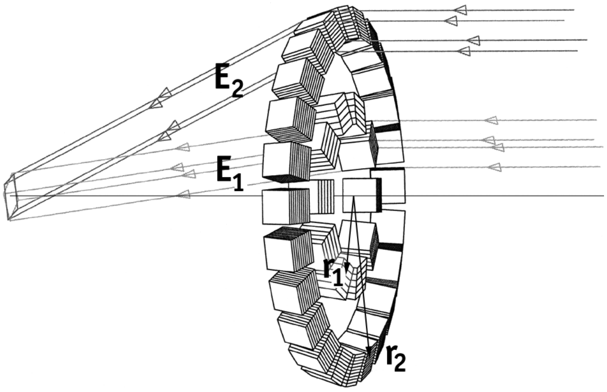

Figure 1 : The basic design of a crystal diffraction lens in Laue geometry

A crystal at a distance r_1 from the optical axis is oriented so that the angle between the incident beam and the crystalline planes is the Bragg angle θ_{B1}. Its rotation of around the optical axis results in concentric rings of crystals. With the same crystalline plane [hkl] used over the entire ring, the diffracted narrow energy band is centered on E_1.

Two subclasses of crystal diffraction lenses can now be identified - *narrow* bandpass Laue lenses and *broad* bandpass Laue lenses.

3.1 NARROW BANDPASS LAUE LENSES

Every ring of crystals uses a different set of crystalline planes *[hkl]* in order to diffract photons in only one energy band centered on an energy $E_1=E_2$. For a given energy E_1, a ring with a radius $r_2 > r_1$ must reflect at an angle $\theta_{B2} > \theta_{B1}$ to concentrate the incident beam at a given focal distance. According to the Bragg condition, this is only possible if the crystalline plane spacing d_2 is smaller than d_1 or if a higher order is used. The ring radii are determined by the Miller indices *[hkl]*. For materials with a cubic unit cell (e.g the face-centered cubic cell of copper, germanium or silicon), the ring radii in small angle approximation are proportional to $\sqrt{h^2+k^2+l^2}$. For a given focal distance f of the lens, r_i is the radius of ring "i",

$$r_i = f \tan [2\theta_{Bi}] \approx f \frac{n\lambda}{d_i}, \qquad (2)$$

where n is the order of the diffraction process, d_i is the crystalline plane spacing of the "i" ring and λ is the wavelength of the radiation to be focused. As the diffraction efficiency generally decreases with increasing diffraction order n, a crystal in an exterior ring will add less efficient area to the lens than a crystal on an inner ring. However, since the number of crystals increases with the ring-radius, all rings will usually contribute about the same amount of efficient area to the lens. Using larger and larger Bragg angles with increasing ring radius allows the instrument to be relatively "compact", featuring a shorter focal length than a broad bandpass Laue lens (see below) with an equivalent amount of efficient area for energy E_1. This type of instrument has been proposed by B. Smither at Argonne National Laboratories[2], and has been developed for use in nuclear astrophysics by the Toulouse-Argonne collaboration[3,4]. The balloon telescope CLAIRE uses a narrow bandpass Laue lens - this instrument is succinctly presented in section 4 below, and discussed in detail in an accompanying paper by H. Halloin et al. (this volume)[5].

3.2 BROAD BANDPASS LAUE LENSES

Only one (or very few) sets of crystalline planes are used in this type of diffraction lens - typically the lowest order planes e.g. *[111]*, with their optimum diffraction efficiency. Since several concentric rings using the *same set* of planes each focussing a slightly different energy because of the varying Bragg angle, a broad energy band can be covered by this type of lens. If the *[111]* crystals of ring 1 are tuned to diffract photons with energy E_1 onto a certain focal point, the *[111]* planes of ring 2 are slightly more inclined with respect to the incident beam in order to reflect an energy $E_2 < E_1$ on the same focal spot. Here, the energy E_i diffracted by each ring is proportional to $1/\theta_i$ or $1/r_i$. As a consequence of the small Bragg angles implied by the low order of diffraction, very long focal lengths are required for a large geometrical lens area.

Diffraction lenses with broad energy bandpass were first proposed, developed and tested for X-rays in the sixties (e.g. Lindquist and Webber[6]). Today, grazing incidence techniques dominate in X-ray astronomy, either with total external reflection or by using multilayer mirrors. N. Lund[7] has proposed a gamma-ray lens with a very broad continuum coverage in which the wide mosaic structure and the alignment of the crystals placed on an Archimedes' spiral results in a effective area between 350 cm^2 at 300 keV and 25 cm^2 at 1.3 MeV.

The MAX mission uses a broad bandpass Laue lens diffracting gamma-rays in two wide energy bands of high relevance for nuclear astrophysics.

3.3 ESTIMATING THE CHARACTERISTICS OF A LAUE LENS

Mosaicity : The mosaic width, or mosaicity, of the crystals governs the flux throughput, the angular resolution and the energy bandpass (see below) of a crystal lens. The acceptance angle of perfect crystals (Darwin width) is extremely narrow (fraction of arcseconds for germanium). The energy bandpass can be increased using so-called mosaic crystals, which are characterized by their mosaic width $\Delta\theta_B$. For a crystal lens telescope, crystals with mosaic widths ranging from a few arc seconds to a few arc minutes are of interest.

In the *Darwin model* for mosaic crystals, the true defect structure of the crystal, which may be due to dislocations, inhomogeneous strains, etc., is described by an agglomerate of perfect crystal blocks. Each block is in itself an ideal crystal, but adjacent blocks are slightly offset in angle with respect to one another. The relative displacements of the blocks are large compared to the Darwin width so that the blocks scatter incoherently. Since the block size is microscopic or sub-microscopic, a large number of blocks take part in the scattering process, and the angular distribution of the blocks can be defined as a continuous function. It is assumed that this function is a Gaussian with a FWHM called the *mosaic width* ω. A thorough description of diffraction in mosaic crystals is given in Zachariasen [8].

Energy bandwidth : The bandwidth for a source on the axis of the lens is determined by the mosaicity of the individual crystals and the accuracy of the alignment of the crystals. By forming the derivative of the Bragg relation in the small angle approximation (Bragg : $2d\theta_B \approx hc/E$),

$$\Delta\theta_B/\theta_B = \Delta E/E \quad , \tag{3}$$

where $\Delta\theta$ is the mosaic width of the crystal; the energy bandpass ΔE of a reflection becomes

$$\Delta E = \frac{2d \cdot E^2 \cdot \Delta\theta_B}{nhc} \quad . \tag{4}$$

Whereas the energy bandpass of a crystal lens grows with the square of energy, Doppler broadening of astrophysical lines (e.g. in SN ejecta) increases linearly with energy for a given expansion velocity.

Crystal diffraction efficiency : As the diffracted photon beam passes through the crystal, photons are diffracted back and forth between the incident beam and the diffracted beam. If the crystal is sufficiently thick, the two beams will emerge from the opposite side of the crystal with equal intensities. The efficiency ε_D of scattering by a mosaic crystal can be defined as the ratio P_H/P_O : the ratio of the "number of reflected photons" to the "number of incident photons". ε_D is the product of an absorption term and a diffraction term :

$$\varepsilon_D = \frac{P_H(T)}{P_O(0)} = 0.5 \cdot e^{-(\mu T/\cos\theta_B)} \cdot \left[1 - e^{-2\alpha T}\right] , \tag{5}$$

where T is the thickness of the crystal. The intensity of the reflected beam from a mosaic crystal is governed by the diffraction coefficient α : its definition is analog to the absorption coefficient μ - the relative power change α due to diffraction in the layer of thickness dT equals the integrated reflecting power of a single block times the probability that the block has the "correct"' inclination times the number of single block layers in dT. Because of multiple reflections and absorption in the crystal, the diffraction efficiency is < 0.5 in the Laue geometry.

4. R&D STEPS TOWARDS MAX

As a first step in the project schedule, a ground-based prototype of a narrow band Laue lens system has been built and successfully tested. It consisted of a diffraction lens focusing 511 keV and 662 keV photons from radioactive sources at finite distances on a small Ge array detector[4]. In order to verify simulations based on the Darwin model for mosaic crystal, the diffraction efficiencies of individual Ge crystals have been measured at the Advanced Photon Source synchrotron at Argonne National Laboratories[9]. Measured diffraction efficiencies range from 20% to 31% according to energy (200 keV - 500 keV) and crystal planes (Ge*[111]* and *[220]*). These results agree with what is expected from the Darwin model. The next logical step towards a space borne crystal lens telescope was CLAIRE : demonstrate, for the first time, a gamma-ray lens for astrophysical observations.

CLAIRE features a narrow band-pass 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 511 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 and the energy band-pass is about 3 keV. The entire payload weighs 500 kg. CLAIRE was launched by the French Space Agency CNES from its base at Gap-Tallard in the French Alps, and was recovered, after nearly 6 hours at float altitude (3 mbar), close to Bergerac in the southwest of France. Since the primary objective of CLAIRE was to prove the principle of a gamma-ray lens under space conditions, the astrophysical target was a "standard candle" - the Crab nebula. CLAIRE's first light consists of about 33 detected photons from the Crab, corresponding to a 3 σ detection. A thorough discussion of CLAIRE and its performance during the 2001 flight is given in the accompanying paper by H. Halloin et al.[5].

As the expected number of Crab photons incident on the 556 crystals of the lens is of the order of 516, the mean efficiency of the CLAIRE lens is about 7%. A peak efficiency of the same order (8.1 %) has recently been measured during a ground-test with an X-ray generator at "quasi infinite" distance (205 m, diffracted energy 165 keV)[5].

While the principle of the Laue lens is now proven for astrophysical observation as well as for ground conditions, the efficiency of CLAIRE is a factor 2-3 lower than that which is calculated for MAX from theory (Darwin model). The modest performance of the CLAIRE lens has two reasons :

a) CLAIRE is a narrow bandpass lens using eight different sets of crystalline planes with theoretical peak efficiencies ranging from 25 % at best ([111] crystalline planes) down to roughly 10% ([333] crystalline planes). Above all, in a narrow bandpass Laue lens the bulk of the crystals are situated in the outer rings - where efficiencies are unfortunately lowest.

b) the quality of the CLAIRE crystals is extremely heterogeneous. Figure 2 shows a histogram with the measured peak fluxes of the individual crystals on the lens. These data have been obtained during crystal tuning with an X-ray generator at 14.2 m distance from the lens - the diffracted energy was consequently 122 keV. Firstly, the histogram illustrates how the efficiency of the crystals of a same ring varies. The spreads by factors of 2 to 10 indicate that the quality of real crystals. The graph also shows that the inner rings ([111] and [220] crystals) are roughly 4 times more efficient than the outer rings ([333] and [440] crystals). A mean peak efficiency of 6.6 % is obtained from the weighted data of the individual crystals. Note that the tuning data (122 keV) will slightly underestimate the efficiency at the nominal energy (170 keV) for which the lens was optimized. Nevertheless, the tuning data prove that real crystals can be as good as the Darwin model predicts : the best crystals of the lens have been measured with peak efficiencies above 20 %.

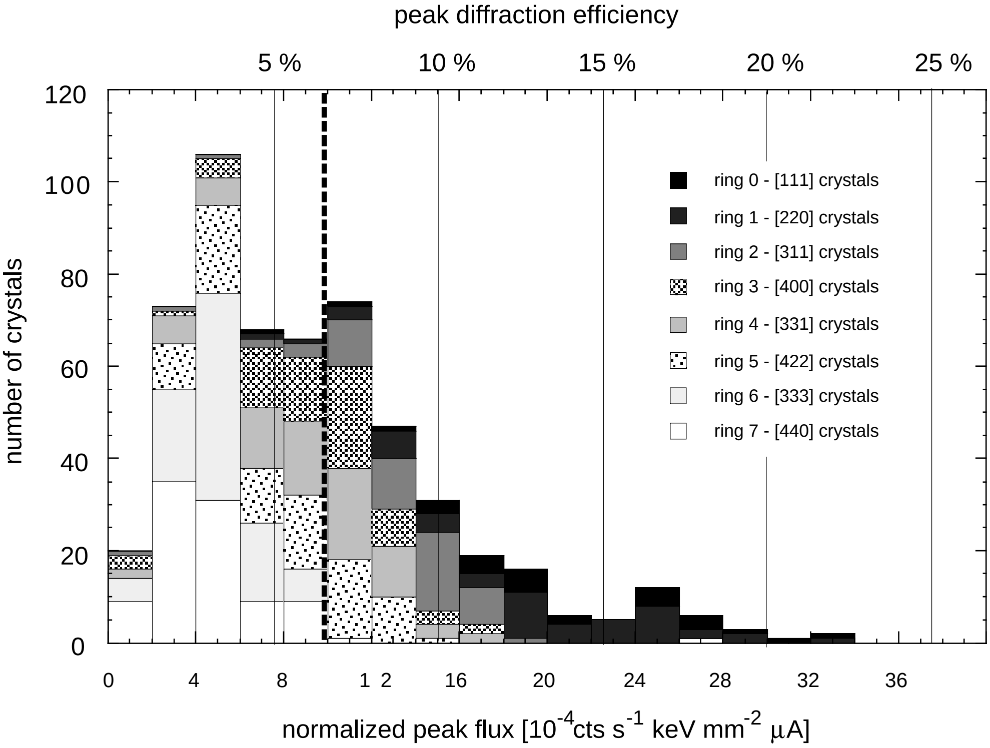

Fig 2. Histogram showing the measured peak fluxes from the individual crystals on the lens. Data have been obtained during the tuning of the lens with an X-ray generator - the tuning energy is 122 keV. The thick dashed line indicates the mean peak efficiency for the entire lens, calculated from the weighted data of the individual crystals.

Gradient crystals : Recent measurements at the synchrotron beam at APS / Argonne Natl. Laboratories have demonstrated the outstanding potential of gradient crystals for a Laue lens. Diffraction efficiencies roughly two times higher than those of our best Ge-Si mosaic crystals were measured in a few sample Si gradient crystals. In these crystals, the gradient in the crystal plane spacing produces a curvature of its planes. When traversing such a crystal, the incident photons will encounter crystal planes satisfying the Bragg condition at a specific depth only. While the chances of being diffracted are optimal in this thin layer, the once deflected beam is unlikely to diffract back into the direct beam since no more crystal planes satisfying the Bragg condition are encountered before the diffracted beam leaves the crystal. With their diffraction efficiency higher than 50 %, gradient crystals - the manufacturing, test and integration of gradient crystals are of foremost priority in our present R&D program.

5. THE MAX MISSION CONCEPT

The mission concept for MAX[1]proposes simultaneous focusing in two broad energy bands of high astrophysical relevance, using two concentric broad bandpass lenses. An outer ring assembly consists of germanium crystals, and an inner ring assembly is made from copper crystals. Its is likely that the ring-assembly will surround the lens spacecraft. The diffracted photons from both the germanium and the copper rings are concentrated onto a 1.5 cm diameter focal spot 133 m from the lens assembly. Here, a small detector (Ge matrix, Si/CdTe, or low temperature calorimeter) shielded by an active BGO shield (thickness 1 cm) performs high resolution spectroscopy. The detector is situated on a small spacecraft flying in formation with the lens spacecraft. A high orbit minimizing gravity gradient disturbances allows long uninterrupted viewing and permits simple passive cooling of the detector to 80-100 K.

5.1 LENS MODULE

As the primary scientific objective of MAX is the study of the ^{56}Ni → ^{56}Co → ^{56}Fe decay chain in type Ia supernovae, the principal energy band is centered on the 847 keV line from ^{56}Co. The corresponding lens is made of copper crystals, each one about 1 cm^3 in size, organized in 10 rings. The crystals of each ring diffract in the *[111]* plane. While the outermost ring of Cu crystals has a radius of 96 cm and focuses energies of 825 keV, the innermost ring has a radius of 87 cm, concentrating photons of 910 keV. Currently copper crystals can be grown with one arcminute mosaicity, so the energy bandpass is about 70 keV with a peak efficiency reaching 15% according to the Darwin model. The total effective lens area at 847 keV is 600 cm^2 (see Fig 3, right side).

The second energy band of MAX is centered on 500 keV, with the objective of studying electron-positron annihilation emission (X-ray binaries, AGN, spectra of SN 1a ...). The width of the energy band permits the observation of redshifted e^+e^- lines from compact objects (eg. the supermassive black hole in the center of our Galaxy), as well as the study of the 478 keV deexcitation line from ^{7}Li. The part of the lens concentrating photons in the 500 keV band is made of 14 concentric rings of germanium crystals on the outside of the Cu one discussed above. The innermost ring has a radius of 97 cm, concentrating photons of 522 keV, the radius of the outermost ring is 110 cm, the diffracted energy being 460 keV. Again, the crystals are each about 1cm^3 in size and use the *[111]* diffraction plane. With their 30 arcsecond mosaicity, the energy bandpass of every ring is about 20 keV while the peak efficiency reaches 25 % (Darwin model). The total effective lens area at 511 keV is 600 cm^2 (Fig 3 left side).

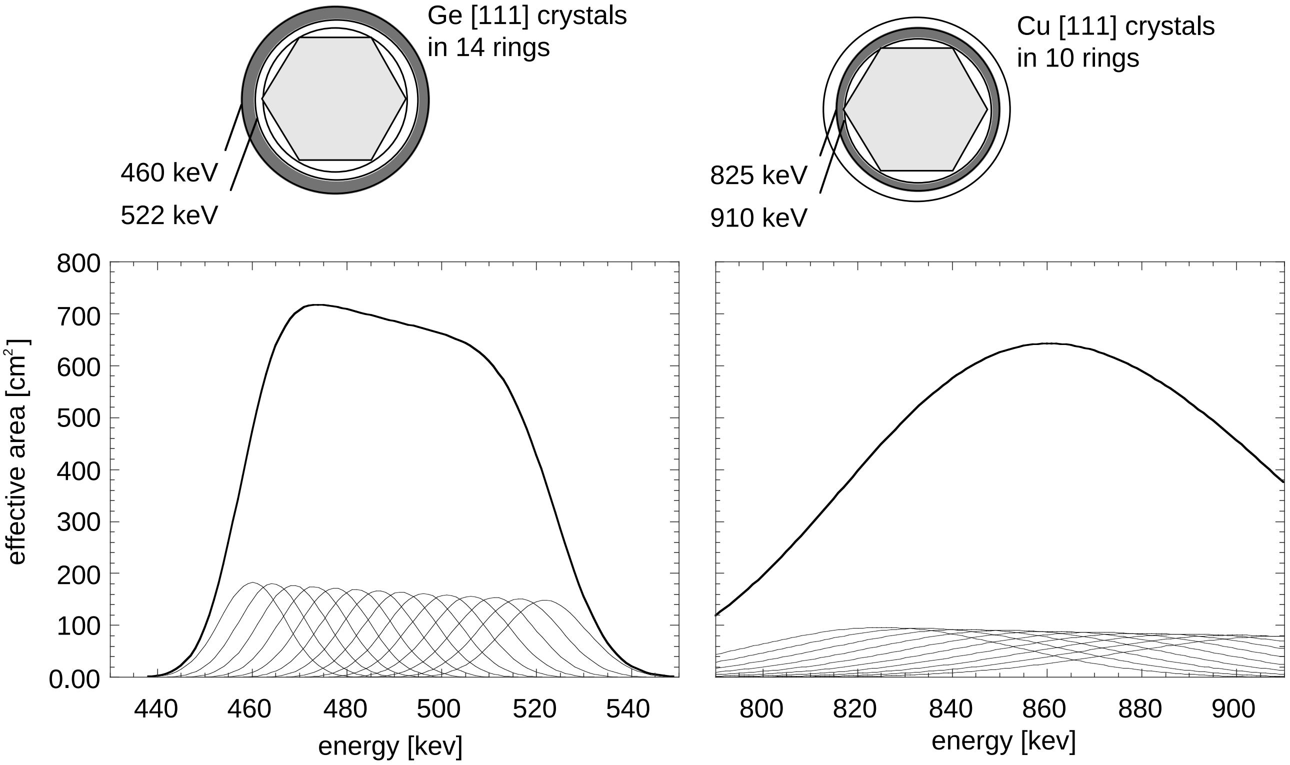

Fig. 3 : The bandpass and effective area of the MAX lens - on the left the exterior 14 rings of germanium crystals, on the right the interior 10 rings of copper crystals. The sketch above each graph depicts the geometry of the rings which are supposed to surround a Protheus type lens spacecraft.

5.2 DETECTOR MODULE

The performance estimates in section 5.3 are based on a single high purity germanium detector (7.5 cm diameter and 7 cm thick) cooled by a passive radiator and actively shielded by BGO scintillators. Aternative solutions include i) a stack of planar Ge detectors using orthogonal strips to provide x-y localization[10], iii) an efficiency optimized narrow FOV Compton Camera featuring Si strips and CdTe pixels[11,12], and iii) an array of low temperature calorimeters (bolometers - detection by the phonons produced by the impinging photons)[13]. Firstly, the imaging capabilities of such systems will facilitate off-axis detections, and secondly a pixelised detector would permit further reduction of the background volume while offering unexposed areas for simultaneous background monitoring.

In the case of the baseline Ge detector, background reduction is performed by analyzing the rise-time and shape of the current pulse : this allows the radial position of the energy deposit to be determined and thus maximum advantage to be taken of the concentrated gamma-ray beam : source counts are necessarily related to interactions in the central volume (R<0.7 cm) which is only a small fraction of the detector volume (≡background volume). Simultaneous background monitoring might be performed by using a redundant Ge detector.

As an option, the background noise could be further reduced by using isotopically enriched ^{70}Ge - this diminishes the internal detector background below 1 MeV by avoiding the (n,β^-) reactions of ^{72}Ge and ^{74}Ge (see ref 14).

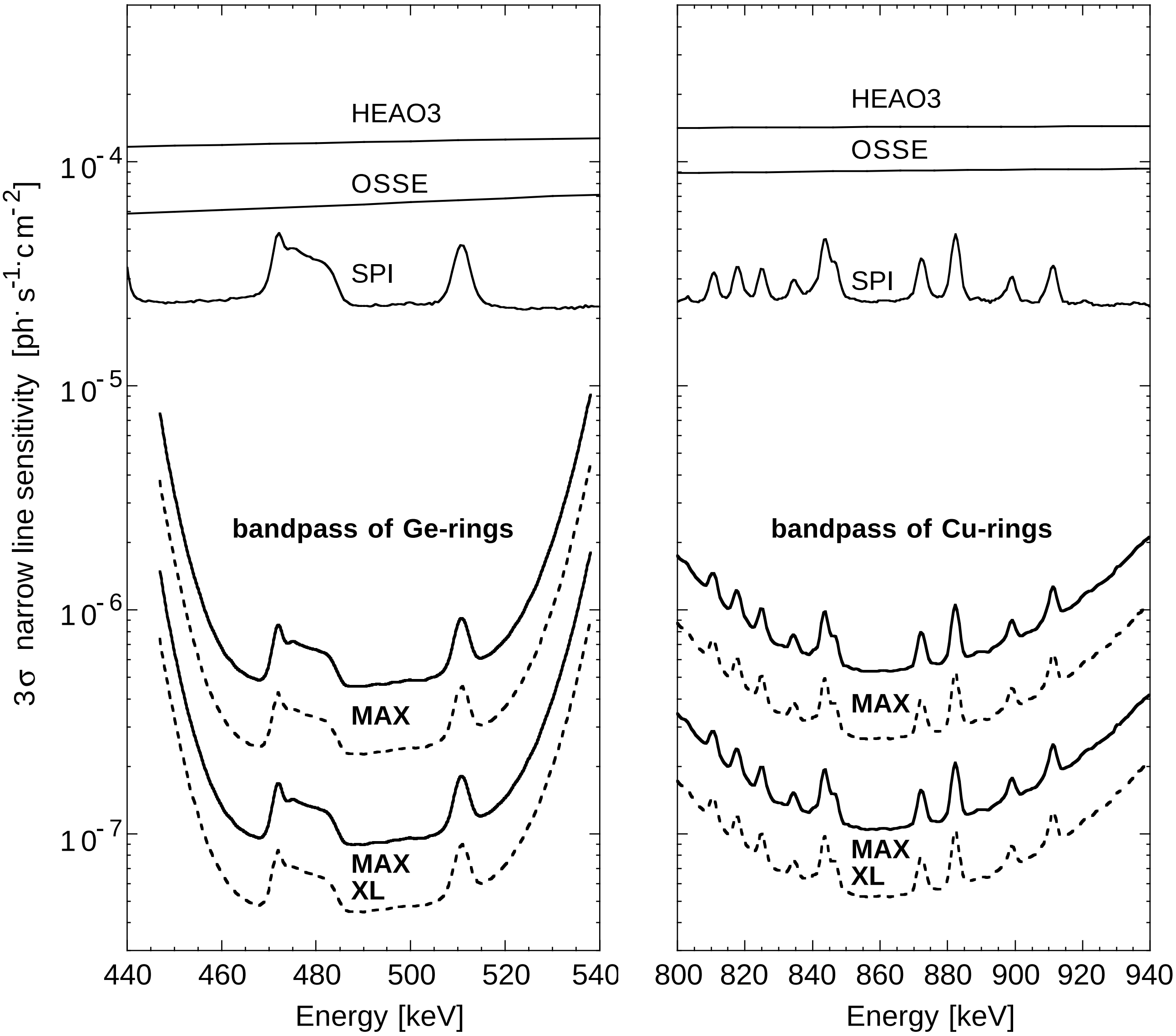

Fig. 4: 3 σ narrow line sensitivity of MAX and MAX XL compared with the achieved sensitivities of precedent missions. The MAX/MAX XL performance is based on the measured detector background of SPI/INTEGRAL; the solid curves stand for diffraction efficiencies of mosaic crystals based on the Darwin model, the dashed curves indicate the potential of recently measured gradient crystals.

5.3 MAX PERFORMANCE

The modeled narrow line sensitivity of MAX in each energy band is shown in Figure 4. The estimate is based on the diffraction efficiency given by the Darwin model (section 4 and 5.1) and a detector efficiency obtained with a complete GEANT mass model of the baseline Ge detector. The specific background rate of the baseline detector (sect 5.2) is the one measured by SPI INTEGRAL[15].

The solid curve in Figure 4 actually represents a conservative estimate for the MAX performance: the background in a single Ge detector on a small freeflying spacecraft will effectively be lower than in the large detector bank of SPI INTEGRAL; also, separating the detector spacecraft from the "bright" lens module strongly reduces the background (maintaining the formation is to be performed by the lens spacecraft) . The potential of the recently measured gradient crystals is sketched by the dashed curves.

A simple demonstration of the performance of MAX is obtained by comparing its effective area and detector background with the corresponding figures of SPI/INTEGRAL: at 511 keV, the effective area of MAX is 350 cm^2, compared to the 93 cm^2 of SPI. MAX therefore collects nearly 4 times more photons from a source than SPI, however its effective volume for background noise is merely 2 x 12 cm^3, 145 times less than SPI. The resulting improvement is $4 \times \sqrt{145} \approx 50$, corresponding to a sensitivity of $10^{-6} cm^{-2} s^{-1}$. In the 847 keV line, the improvement is of the same order resulting in a sensitivity of $8 \cdot 10^{-7} cm^{-2} s^{-1}$.

Scaling the linear dimensions of MAX by a factor s will improve the sensitivity by a factor s^2. As well as the sensitivity for the baseline version of MAX (outer / inner radius of the ring lens : 111 cm / 86 cm, focal length : 133 m), Fig 4 shows the performance of a version for "MAX XL" - with an outer diameter of the ring-lens of 5 m (outer / inner radius of the ring lens : 250 cm / 193 cm, focal length : 300 m) : as the lens surface is increased by a factor five, the performance is improved by a factor five.

Although a crystal lens telescope is not a direct imaging system, MAX will be able to generate intensity maps by sweeping the telescope optical axis over a limited target area, or by using its off-axis response for broadened line sources. The angular resolution of a crystal lens telescope is determined by the mosaic width of the crystals, as well as the energy resolution of the detector - here the angular resolution is of the order of 45 arcseconds at 511 keV, and about 90 arcseconds at 847 keV. The imaging capabilities of broad bandpass Laue systems have been discussed by Lund[7]. The capability of Laue lenses to resolve possible e^+e^- sources associated with the radiojets of the microquasar 1E1740-29[16] at 511 keV has been demonstrated by extensive simulations[17].

5.4 OPTICAL MONITOR

MAX is to be equipped with an optical monitor (OM) that provides contemporaneous high precision ($\Delta v=0.02$ at $v=16^m$) multicolour (VRI) photometry for the pointed target. Its good angular resolution (2") will allow for a clear separation of supernova light from host galaxy emission, while the large field of view (35') will permit simultaneous observation of galactic reference stars for photometric calibration. The OM is intended to supplement the gamma-ray data with precise and well sampled optical and infrared data (in particular supernova lightcurves).

5.5 FORMATION FLYING

The MAX project presents a number of complex challenges for spacecraft engineering : 1) the *lens module* must be able to point and maintain the lens axis to within 15 arcsec of the target. As SNe and other targets of opportunity may occur in any direction, there should be as few viewing constraints as possible. 2) the *detector module* must have a sensory and control system enabling it to attain and maintain a precise relative lateral position (± 1 cm) at a focal distance of 133 meters (± 1 m) and rough target pointing (few degrees). The master-slave geometry used for MAX is called "Non-Keplerian Formation Flying" because at least one of the satellites orbit must be continuously controlled. Since formation-flying is rapidly developing into a major area of activity in space science, various technologies are presently being developed for ambitious future space projects (XEUS, LISA, DARWIN, MAXIM etc).

A preliminary mission analysis has been conducted by ALCATEL SPACE for various types of operational orbits, namely a low-Earth orbit and a HEO[18]. The guidance laws to fulfill the constraints imposed by the MAX formation were derived and appear to be compatible with existing low-thrust propulsion technologies for both types of orbits.

6. CONCLUSION

The sensitive gamma-ray spectroscopy performed by MAX addresses a wide range of fundamental astrophysical questions such as the life cycles of matter and the behavior of matter under extreme conditions: The primary scientific objective of MAX is the study of type Ia supernovae by measuring intensities, shifts and shapes of their nuclear gamma-ray lines. Secondary objectives include galactic microquasars (e+e- annihilation radiation from the jets), neutrons stars and pulsars, X-ray Binaries, AGN, solar flares and gamma-ray burst afterglow.

MAX constitutes a breakthrough for the study of compact sources by combining narrow line sensitivities of 10^{-6} to 10^{-7} $ph \cdot s^{-1} \cdot cm^{-2}$ with high energy resolution ($E/\Delta E \approx 500$) and very good positioning. MAX features a Laue lens consisting of rings of Cu and Ge crystals, covering simultaneously two broad energy ranges : 810-900 keV for the observation of the ^{56}Ni decay chain in type Ia SN, 450-530 keV for the observation of e^-e^+ emission and the ^{7}Li line. A small detector, maintained at a distance of 133 m by a second spacecraft flying in formation, collects the focused radiation.

The R&D program lead by our collaboration - particularly the CLAIRE mission - has demonstrated the feasibility of a space borne Laue lens for nuclear astrophysics.

ACKNOWLEDGEMENT

The authors are grateful to the members of the MAX Scientific Advisory Group who have helped greatly in evaluating the scientific requirements and prospects for a focusing gamma-ray telescope. This work was supported by the U.S. Department of Energy, Basic Energy Sciences, under contract no. W-31-109-Eng-38. The team at CESR acknowledges continuing support from the French Space Agency CNES.

REFERENCES

1. von Ballmoos, P., et al, 2002, CNES proposal
2. Smither, R.K., 1982, Rev. Sci. Instr. **44**, 131
3. von Ballmoos, P., Smither R.K., 1994, Astrophys. J. Suppl., **92**, 663
4. Naya, J.E., 1996, *Nuclear Instr. And Meth.. Sect. A,* **373**, 59
5. Halloin, H., et al, 2003, this volume (SPIE Vol. **5168**)
6. Lindquist, T.R. ,and Webber, W.R, 1968, Can. J. Phys, **46**, 1103
7. Lund, N., 1992, *Exp. Astron*. **2**, 259
8. Zachariasen, W.H., 1946, *Theory of X-ray diffraction in Mosaic Crystals*, Wiley & Sons
9. Kohnle, A., et al., 1998, *Nuclear Instr. And Meth.. Sect. A* ,Vol. **416**, 493
10. Boggs, S. E., et al., 2003, SPIE proc. (Intl. Soc. for Optical Engeneering), Vol. 4851, p.1221, 2003
11. Takahashi, T., 2003, New Astronomy Reviews, to be published
12. Limousin, O., 2003, NIM A, **504**, 24-37
13. Giuliani, A., 2001, Proc. SPIE Vol. **4507**, 203
14. Gehrels, N., Nucl. Instr. and Meth., 1990, **A292**, 505
15. Jean, P., et al., 2003, A&A, to be published
16. Mirabel ,F.,et al., 1992, *NATURE*, **358**, No 6383
17. Kohnle, A., 1998, Phd Thesis, Université Paul Sabatier, Toulouse
18. Martinot V., et al. 2003, proc 3rd Intl Workshop on Satellite Constellations and Formation Flying, Pisa, Feb 2003