The MAX mission : focusing on high sensitivity gamma-ray spectroscopy

P. von Ballmoos(1), H. Halloin(1*), J. Paul(2), N. Abrosimov(3), K. Andersen(4), P. Astier(5), S. Basa(6), D. Barret(1), P. Bastie(7), A. Bazzano(8), A. Bignami(1), A. Blanchard(9), B. Cordier(2), T. Courvoisier(10), P. Courtois(4), A. Ealet(6), B. Hamelin(4), M. Harris(1), M. Hernanz(11), J. Isern(11), P. Jean(1), J. Knödlseder(1), Ph. Laurent(2), F. Lebrun(2), X. Leyre(12), O. Limousin(2), A. Marcowith(1), V. Martinot(12), A. Mazure(6), L. Natalucci(8), J.-F. Olive(1), R. Pain(5), S. Paltani(6), N. Prantzos(13), H. Riemann(3), R. Sadat(9), H. Sainct(12), G. Skinner(1), B. Smither(14), P. Ubertini(8), F. Vedrenne(1), G. Weidenspointner(1)

(1)CESR, 9, av. du Colonel-Roche, 31028 Toulouse, France
(2)Service d'Astrophysique, CEA- Saclay, 91191 Gif sur Yvette, France
(3)Institut für Kristallzüchtung, Max-Born-Str. 2, 12489 Berlin, Germany
(4)Institut Laue-Langevin, BP 156, 38042 Grenoble, France
(5)LPNHE, 4, place Jussieu, Tour 33, 75252 Paris, France
(6)LAM, Traverse du Siphon-Les trois Lucs, 13376 Marseille, France
(7)Laboratoire de Spectrométrie Physique, BP 87, 38402 St Martin d'Hères, France
(8)IAS, Via del Fosso del Cavaliere, 100, 00133 Roma, Italy
(9)LA-OMP, 14, Avenue Edouard-Belin, 31400 Toulouse, France
(10)ISDC, Chemin d'Ecogia 16, 1290 Versoix, Switzerland
(11)IEEC, Edif. Nexus, 08034 Barcelona, Spain
(12)Alcatel Space Industries, 26, av Champollion, 31037 Toulouse, France
(13)IAP, 98bis, bd Arago, 75014 Paris, FRANCE
(14)Argonne Natl. Lab, 9700 South Cass Avenue, Argonne, Il, 60439, USA

ABSTRACT

The mission concept MAX is a space borne crystal diffraction telescope for nuclear astrophysics. With its Laue lens consisting of Cu and Ge crystals, MAX is capable of concentrating gamma-rays onto a small, low background detector, situated on a spacecraft flying in formation. MAX observes simultaneously in two energy bands of high astrophysical relevance (450-530 keV and 800-900 keV); its effective lens area in each band is roughly 600 cm^2. A small position sensitive detector (strip Ge detector, Si/CdTe matrix, or single segmented Ge detector) performs high resolution spectroscopy and provides the capability for measuring the polarization of the incident photons.

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 in the 800-900 keV energy band. When finally understood and calibrated, these profoundly radioactive events will be crucial in measuring the geometry and evolution of the entire Universe. Observing the radioactivities from a substantial sample of supernovae and novae will significantly improve our understanding of explosive nucleosynthesis.

Moreover, sensitive gamma-ray line spectroscopy performed with MAX is expected to clarify the nature of sources of e^-e^+ annihilation radiation which would appear in the 450-530 keV band, including jets in Galactic microquasars, neutrons stars and pulsars, X-ray Binaries, AGN, solar flares and, gamma-ray afterglow from gamma-burst counterparts. Last but not least, MAX' capability for measuring polarization might be crucial in resolving the "MeV blazar" problem.

Keywords : instruments for nuclear astrophysics, gamma-ray optics

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

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[*] present address : MPI für Extraterrestrische Physik, Postach 1312, Garching, Germany

improving the sensitivities by an order of magnitude, 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 of existing space transportation systems, 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 for our gamma-ray lens, 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} ph·s^{-1}·cm^{-2} with high energy resolution ($E/\Delta E \approx 500$) and very good positioning.

2. THE SCIENTIFIC CASE

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 are 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 two dedicated MAX meetings (“rencontres de Moriond” 2002, INTEGRAL workshop 2004), the mission concept for MAX 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 $^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$ 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. 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.

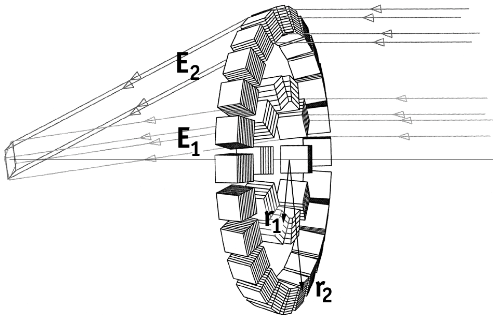

Figure 1 : The basic design of a crystal diffraction lens in Laue geometry.

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 around the optical axis results in concentric rings of crystals (Fig 1). 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 Smither (1982) and has been developed for use in nuclear astrophysics by the Toulouse-Argonne collaboration (von Ballmoos and Smither, 1994, Naya et al.1996). 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. (2004, this volume).

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 all concentric rings use the *same set* of planes, each ring focuses a slightly different energy because of the varying Bragg angle. This way, 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, 1968) Today, grazing incidence techniques dominate in X-ray astronomy, either with total external reflection or by using multilayer mirrors. N. Lund (1992) 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 proposed 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* η. A thorough description of diffraction in mosaic crystals is given in Zachariasen (1946).

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 : $2d\theta_B \approx hc/E$),

$$\Delta\theta_B/\theta_B = \Delta E/E \quad , \qquad (3)$$

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

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

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 :

$$\varepsilon_D = \frac{P_H(T)}{P_O(0)}$$

$$= 0.5 \cdot e^{-(\mu T/\cos\theta_B)} \cdot \left[1 - e^{-2\sigma T}\right] \quad , \qquad (5)$$

where T is the thickness of the crystal. The intensity of the reflected beam from a mosaic crystal is governed by the diffraction coefficient σ : its definition is analogue to the absorption coefficient μ - the relative power change σ 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 (Naya et al 1996). In order to verify simulations based on the Darwin model for mosaic crystals, the diffraction efficiencies of individual Ge crystals have been measured at the Advanced Photon Source synchrotron at Argonne National Laboratories (Kohnle et al. 1998). 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 : to demonstrate, for the first time, a gamma-ray lens for astrophysical observations.

4.1 CLAIRE 2001

The R&D project 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. The entire payload weighs 500 kg. On June 14 2001, 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. In 72 minutes of good pointing, about 33 photons from the Crab were detected in the 3 keV "wide" energy bandpass. CLAIRE's first light ! The 3 σ detection corresponds to a peak efficiency of about 12.5±4 % (assuming a bandpass of 3 keV FWHM, based on the measured mosaicities of the individual crystals). A thorough discussion of CLAIRE and its performance during the 2001 flight is given in the accompanying paper by Halloin et al (2004).

4.2 CLAIRE TGD

In May 2003 the CLAIRE telescope was tested on a 205 m optical bench, set up on a small airfield near Figueras in northern Catalonia. At this "quasi infinite" distance the diffracted energy is 165 keV. Making use of an industrial X-ray generator (300 kV) a peak efficiency of 9.7±0.3% was measured, confirming the lens simulations and the results of the balloon flight. For a comprehensive discussion of the CLAIRE TGD (test à grande distance) see Alvarez et al. (2004, this volume).

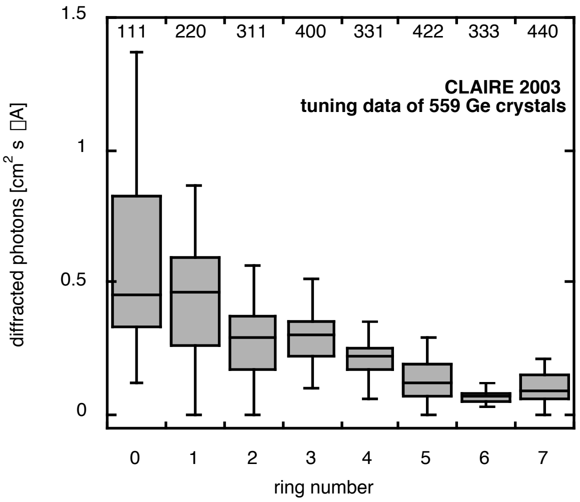

Fig 2 : Box diagram showing the spread of the measured fluxes from 559 individual Ge crystals. Data have been obtained during the tuning of the lens with an X-ray generator (tuning energy is 122 keV). Boxes enclose 50% of the data set of each ring, upper/lower limits are ± 25 % from the median value of the flux which is displayed as a line. The lines extending from the top and bottom of each box mark the minimum and maximum values within the crystal data set of each ring.

At present, the principle of the Laue lens can be considered proven for astrophysical observation as well as for ground conditions. However the efficiency of CLAIRE is a factor 2-3 lower than that which is calculated 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). During crystal tuning (with an X-ray generator at 14.2 m distance from the lens) a diffracted flux has been measured for every individual crystal on the lens. The box diagram in Figure 2 compares the statistics of these fluxes in the eight rings. The data show that the inner rings ([111] and [220] crystals) are roughly 4 times more efficient than the outer rings ([333] and [440] crystals). Note that 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 illustrates the very important spread of the measured fluxes in a single ring. The efficiency of the individual crystals using the same planes and geometry varies by factors of 2 to 10 !

Despite the above inadequacies, 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 %.

5. THE MAX MISSION CONCEPT

The present MAX mission concept has been proposed in response to the call for ideas for a "formation flying missions" issued by the French space agency CNES in January 2004 (von Ballmoos et al., 2004). MAX features simultaneous focusing in two broad energy bands of high astrophysical relevance. Its Laue lens is a ring assembly of germanium and copper crystals surrounding the lens spacecraft. Incident photons are concentrated onto a small focal spot 86 m from the lens assembly. Here, a small detector, situated on a formation flying spacecraft, performs high resolution spectroscopy and provides the capability for measuring the polarization of the incident photons.

5.1 Lens Module

The lens is composed of 8200 crystals of copper and germanium, each exposing a geometric surface of 1.5x1.5 cm to the incident beam. The crystals are organized in 24 concentric rings occupying radii between 56-80 cm and 96-111 cm - their total weight is about 150 kg. The thickness of the crystals (about 1 cm), their mosaicity (30") and the size of the crystallites (100 □) characterize the performance of the individual rings. For rings made from Cu crystals, the peak efficiency is estimated to be 25 % for a bandpass of typically 42 keV. The peak efficiency and bandpass for Ge crystals are 29 % and 17 keV, respectively.

In the principal energy band, centered on the 847 keV line from ^{56}Co, the bandpasses of 10 Cu rings and 3 Ge rings superimpose to cover an energy band from 800-920 keV, with a cumulated effective surface of 500 cm^2 at 847 keV. In the second energy band dedicated to the e^-e^+ annihilation line, the bandpasses of 9 Cu rings and 2 Ge rings combine to cover an energy band from 450-540 keV, with a cumulated effective surface of 800 cm^2 at 511 keV.

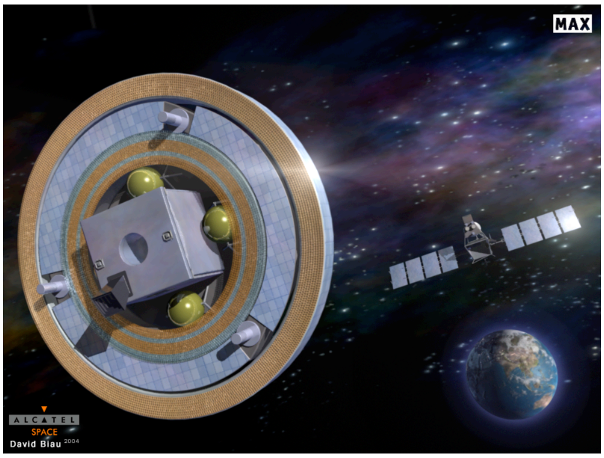

Fig 3 : Artists view of the MAX. In the foreground : the lens spacecraft surrounded by concentric rings of copper and germanium crystals, in the background the detector spacecraft.

5.2 Detector Module

The baseline detector for MAX is a stack of planar Ge detectors using orthogonal strips. Alternative solutions include i) a single high purity germanium detector (SPI/INTEGRAL type) cooled by a passive radiator and actively shielded by BGO scintillators, ii) an efficiency optimized narrow FOV Compton Camera featuring Si strips and CdTe pixels (Takahashi 2003, Limousin 2003), and iii) an array of low temperature calorimeters (detection of phonons produced by the impinging photons, Giuliani, A., 2001).

The advantages of using a detector providing localization of the interactions are multiple : besides following the excursions of the focal spot across the detector plane, such a system facilitates off-axis detections and offers unexposed areas for simultaneous background monitoring. Most importantly, in a system with 3-dimensional event localisation, a dramatic further background reduction can be performed by reconstructing the arrival direction of the photons using Compton kinematics. In this way, only photons with event circles intersecting the Laue lens are selected as source events. The performance estimates in section 5.3 are based on a stack of four planar Ge detectors using orthogonal strips to provide x-y localization and fast electronics to measure the depth of the interaction in the detector layer. (Boggs et al. 2003).

5.3 Max Performance

The modelled 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). For the baseline detector (a), a semi-empirical model based on measured data from the unshielded TGRS Ge detector and scaled for background reduction using the Compton kinematics is used. The option (b) uses the specific background rate of a SPI INTEGRAL Ge detector (Jean et al., 2003).

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; for MAX we expect an angular resolution of the order of 45 arcseconds.

The imaging capabilities of broad bandpass Laue systems have been discussed by Lund (1992). The capability of Laue lenses to resolve possible e^+e^- sources associated with the radiojets of the microquasar 1E1740-29 (Mirabel et al. 1992) at 511 keV has been demonstrated by extensive simulations (Kohnle 1998).

5.4 Monitors

Several options of monitors could supplement the gamma-ray data of MAX. An optical monitor (MOV) would provide contemporaneous high precision (σ_v=0.02 at v=16^m) multicolour (VRI) photometry for the pointed target (in particular supernova lightcurves). Good angular resolution (2") would allow for a clear separation of supernova light from host galaxy emission, while the large field of view (35’) would permit simultaneous observation of galactic reference stars for photometric calibration.

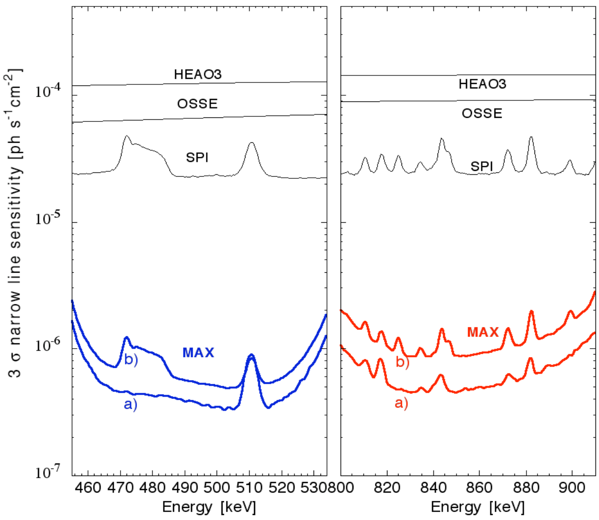

Fig. 4 : 3 σ narrow line sensitivity of MAX compared with the achieved sensitivities of earlier missions. The MAX performance is based on (a) the background of the TGRS Ge detector, scaled for background reduction using the Compton kinematics, and (b) on the measured background of the SPI/INTEGRAL Ge detectors.

An X-ray monitor (MOX) would only require a coded mask in the central parts of the lens spacecraft since a well suited detector already exists in the form of the first layer of the stack detector. Besides of its excellent performance (angular resolution of 5 arcsec in a completely coded field of view of 3 arcmin, and an efficient area of 50 cm^2 between 10-100 keV) this option would allow one to directly verify the alignment of the two satellites by detecting the high energy emission of the source.

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 supernovae 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 86 meters (± 0.1 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 mission analysis of MAX has been conducted by ALCATEL SPACE for various types of operational orbits, namely for a HEO (highly elliptical orbit), a circular three day orbit, and an orbit around L2, the second Lagrange point (Martinot 2003). The guidance laws to fulfil the constraints imposed by the MAX formation have been derived and appear to be compatible with existing low-thrust propulsion technologies for the proposed 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 behaviour 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. Figure 5 indicates that the detection of 3-8 supernovae can be expected per year of operation. 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 SNIa 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.

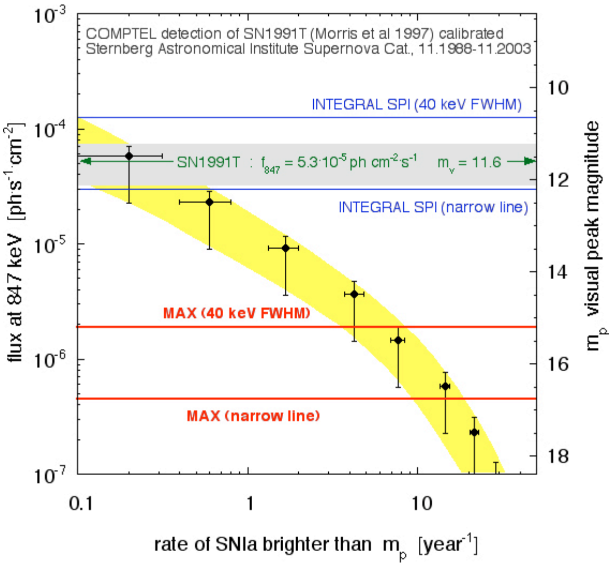

Fig. 5 : The estimated ^{56}Co line of type Ia supernovae that have a visual peak magnitude brighter than m_p. The correspondence between peak magnitude and gamma-ray flux is based on the COMPTEL detection of SN1991T (Morris et al 1997). Asymmetric error bars are due to the systematic uncertainties in the peak magnitude of SN1991T. The SNIa rate are from the "Sternberg Astronomical Institute Supernova Catalogue" between November 1988 and November 2003.

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

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