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ORIGINAL ARTICLE

The SIMBOL-X hard X-ray mission

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Abstract SIMBOL-X is a hard X-ray mission based on a formation flight architecture, operating in the 0.5–80 keV energy range, which has been selected for a comprehensive Phase A study, being jointly carried out by CNES and ASI. SIMBOL-X makes uses of a long (in the 25–30 m range) focal length multilayer-coated X-ray mirrors to focus for the first time X-rays with energy above 10 keV, resulting in at least a two orders of magnitude improvement in angular resolution and sensitivity compared to non focusing techniques used so far. The SIMBOL-X revolutionary instrumental capabilities will allow us to elucidate outstanding questions in high energy astrophysics, related in particular to the physics and energetic of the accretion processes on-going in the Universe, also performing a census of black holes on all scales, achieved through deep, wide-field surveys of extragalactic fields and of the Galactic center, and the to the acceleration of electrons and hadrons particles to the highest energies. In this paper, the mission science objectives, design, instrumentation and status are reviewed.

Keywords Hard X-ray telescopes · X-ray astronomical optics · Multilayer mirrors · X-ray detectors · Formation flying

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1. Introduction

With the increase power of space observatories, high energy emission has been observed from objects of all scales in the Universe, from compact sources such as black holes to diffuse hot plasma pervading galaxies and clusters of galaxies, revealing violent processes which are thought to play a major role in the dynamics of these objects. These processes pertain to the two domains of accretion physics and particle acceleration mechanisms. In accretion physics, the accretion of matter onto Black Holes is a fundamental astrophysics topic. Identifying and understanding this phenomenon has indeed profound implications both on physics, since the Black Hole environment is the only place which allows tests of General Relativity beyond the weak-field limit, and on cosmology since the accretion luminosity may dominate the radiant energy of the Universe emitted since the big-bang (this topic was particularly well addressed in the presentation of the scientific case for the HEXIT-SAT mission by Fiore et al. [1]). The second domain is also fundamental for astrophysics. One still lacks firm evidences of hadron acceleration in suspected astronomical sites (despite clearly seeing huge electron accelerations), and one still looks for the origin of the highest energy photons and cosmic rays which have been observed by ground experiments as e.g. the HESS and MAGIC Cherenkov telescopes [2, 3]. Identifying the processes at work in acceleration sites, as supernovae remnants or jets, and finding their limit is a key question in this issue. These processes are best revealed and characterized by their non thermal-emission in the low energy X-ray and hard X-ray domains, the latter probing the most energetic and violent environments.

There is however a very large gap in angular resolution and sensitivity between these two domains. Below ~10 keV, astrophysics missions are using X-ray mirrors based on grazing incidence reflection properties. This has allowed increasing by orders of magnitude the discovery space for compact accreting sources, for galaxies with an active nucleus and for high temperature thermal plasma sources. The use of collimated detectors on board the UHURU, Ariel-V, and HEAO1 satellites in the 1970 decade led to the discovery of <1000 X-ray sources in the whole sky, most of which with a redshift $z < 0.5$. Imaging detectors, first on board Einstein and then ROSAT, produced the first systematic observations of AGNs up to $z = 2$–3, and systematic mapping of galaxies, clusters of galaxies and supernova remnants. The superior image quality of Chandra and the high throughput of XMM-Newton have expanded the discovery space even further, resolving for example more than 80% of the cosmic X-ray Background below 5–6 keV, and starting to probe emission of star-forming galaxies, and to resolve jets lobes and hot spots in quasars and radio galaxies. Above 10 keV however, the situation contrasts strikingly with this picture. The most sensitive observations so far have been performed by a collimated instrument, the BeppoSAX PDS [4] and by coded mask instruments such as the INTEGRAL IBIS/ISGRI [5] and the Swift BAT [6]. Only a few hundred sources are known in the whole sky at $E > 10$ keV, a situation recalling the pre-Einstein era during the 1970s. More than two orders of magnitude are separating the sensitivity and angular resolution in hard X-rays compared to the one that is achieved in X-ray telescopes. This huge gap is entirely due to the fact that until recently there was no technology available to build a focusing instrument in hard X-rays. The ambition of the proposed hard X-ray pointed telescope, SIMBOL-X [7] is to utilize recent breakthroughs in the development of hard X-ray optics to assemble a large-area, high-resolution focusing telescope. To meet these objectives SIMBOL-X relies on the combination of the emerging “Formation Flying” technology, which allows the use of very long focal length optics, and of multilayer reflection mirror technology, providing the required sensitivity at high X-ray energies. These technological innovations offer a gain of roughly two orders of magnitude

Table 1 SIMBOL-X top-level scientific requirements

Parameter	Requirement
Energy band	$\sim$0.5–>80 keV
Field of view – FWHM (at 30 keV)	$9'$–$13'$ (diameter)
On-axis effective area	$>1000\,\mathrm{cm}^2$ at <2 keV**
	$>600\,\mathrm{cm}^2$ at 8 keV
	$\sim450\,\mathrm{cm}^2$ at 20–40 keV
	$>100\,\mathrm{cm}^2$ at 70 keV
On-axis sensitivity	$<1\,\mu$Crab (3σ 1 Ms) at 20–40 keV
Line sensitivity at 68 keV	Better than 10^{-3} cts/s/keV
Angular resolution (HPD)	$\sim$15”, <20”
Spectral resolution	E/ΔE 40–50 at 6–10 keV
	E/ΔE = 50 at 68 keV (goal)
Absolute timing accuracy and Time resolution:	100 μs (50 μs goal)
Absolute pointing reconstruction	$\sim$2 (radius, 90%,TBC)
Mission duration	3 yrs including commissioning and calibrations (at least 2 yrs of scientific program)

in sensitivity and angular resolution compared to the current instruments above 10 keV. In addition to this fundamental breakthrough in hard X-rays, SIMBOL-X will have a low energy threshold around ~0.5–1 keV, which will allow to fully cover the spectral transition from thermal to non-thermal emission as well as the Iron line spectral band, two important characteristics for the study of the highly variable accreting sources which are among the prime scientific goals of this mission. SIMBOL-X will offer an improvement of roughly two orders of magnitude in sensitivity and angular resolution compared to the instruments currently operating above 10 keV.

This large gain in performance will allow SIMBOL-X to effectively address all the crucial scientific issues identified in a Top Level Requirements document jointly prepared by French and Italian scientists. The Top level scientific requirements are reported in Table 1. In particular, SIMBOL-X will be able to resolve up to the 65% of the cosmic X-ray background light into discrete sources in the spectral band where the cosmic power is maximum, finally solving the problem of the spectral paradox and revealing the exact nature of the sources that make the X-ray background. SIMBOL-X will operate in the time-frame 2013–2016 as a world-class X-ray facility providing a factor 2 better sensitivity and angular resolution combined with broader wavelength coverage even compared to similar efforts that may operate before the year 2010.

As already mentioned, in addition to this fundamental breakthrough in hard X-rays, SIMBOL-X will have a low energy threshold around ~0.5–1 keV, which will ensure full spectral coverage of the transition from thermal to non-thermal emission as well as the Iron line spectral band, two important characteristics for the study of the highly variable accreting sources which are prime scientific targets of this mission.

2. The mission concept

The SIMBOL-X mission from system architecture point of view is the subject of another paper of these proceedings [8]. For sake of completeness, a few details are reported hereafter. The two satellites forming the SIMBOL-X space mission will be launched by a Soyuz rocket

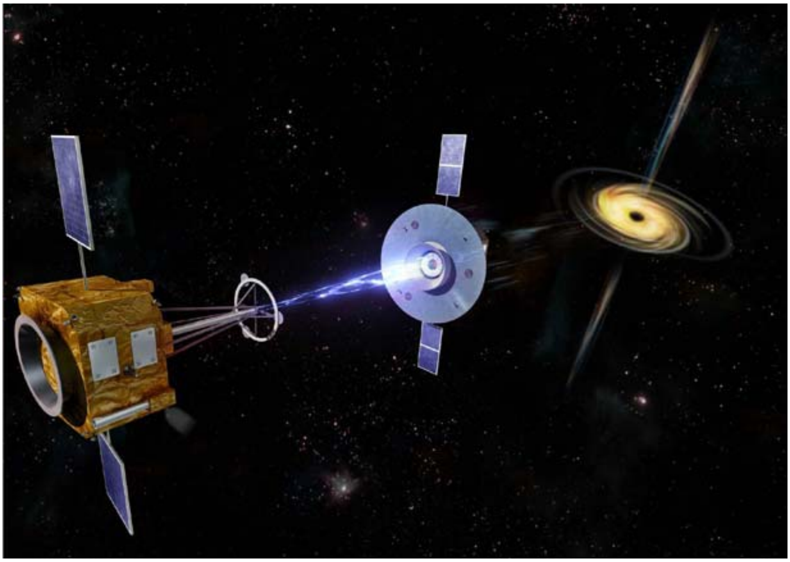

Fig. 1 A sketch of the SIMBOL-X focusing telescope based on two different satellites (one hosting the optics module, the other the focal plane) in a "formation flight" configuration. It should be noted the presence of the two passive shielding systems, the "sombrero-like" and of the long collimator baffles (surrounding the optics and on the top of the detector plane respectively), implemented to limit the opening angle to the sky of the focal plane (Credits: CNES)

with a Fregat upper stage. Both vehicles will be injected in a high elliptical orbit to minimize the particle background, being also the perigee outside the Val Allen belts. In the Phase 0 study carried out by CNES in 2005, the orbit has a perigee of 44,000 km and an apogee of 253,00 km at launch. In observation mode, the relatively heavy mirror satellite (master) maintains its orbit, while the detector satellite (slave) is positioned along the mirror axis, keeping the distance between the mirror and the focal plane assembly at the focal plane value.

SIMBOL-X is basically built using a classical Wolter I optics focusing X-rays onto a focal plane detector system. The gain in maximum energy is achieved by having a long focal length, in the 20–25 m range, i.e. $\sim$3 times larger than the XMM–Newton mirrors. In this way it is possible to make use of a mirror module with the same external diameter as XMM, but with mirror reflecting angles much smaller ($\sim$3 times less), able i.e. to efficiently reflect also in the hard X-ray domain. Since the a focal length of a few tens meters cannot fit in a single spacecraft, the mirror and detectors will be flown on two separate spacecrafts in a formation flying configuration, as sketched on Figure 1.

SIMBOL-X is a pointed telescope, which is nominally required to be able perform very long uninterrupted observations (10^5 s or more) on the same target. The necessity to have a stable image quality, as well as to keep the full field of view inside the detector area, dictates the requirements on the formation flying stability. The constraint is that the distance between the two spacecrafts (along the telescope axis) must be kept at the focal length value within about ± 10 cm, whereas the intersection of the telescope axis must be at the centre of the focal plane within about ± 20 arcsec. It is also required that the arrival direction of each detected photon can be reconstructed to ± 2 arcsec (radius, 90%), which imposes a knowledge (monitoring) of the relative positions of the two spacecrafts to that level of accuracy.

There are three main components in the SIMBOL-X payload. The first one is the optics based on grazing incidence mirrors. It should be noted that in the initial design a Pt single layer coating was assumed, characterized a maximum threshold energy of ∼50 keV, and a Field-of-View (FOW) at 30 keV of ∼6 arcmin Full-With-at-Half-Maximum (FWHM). However, in order to be fully compliant with the new Top Level Requirements reported in Table 1, which assumes a much larger energy operative range (up to 80 keV at least) and FOV (in the 9–13 arcmin FWHM range) with respect to the initial baseline, now the Pt coating has been replaced by a multi-layer Pt/C coating, while the focal length has been reduced in the 20–25 m range (the final value will be defined at the end of the on-going phase A study). The second component is the focal plane that, to cover a very broad energy operative range (0.5–80 keV), will be based on two different solid-state detectors in stack configuration, the first one based on macropixel arrays made of Si (effective from 0.5 up to 10 keV), and the other on Cd(Zn)Te (effective from 10 keV up to 100 keV). It should be noted that Si is sufficiently transparent in the hard X-ray region to allow the hard X-ray photons to pass towards the first detector without being absorbed. A third fundamental component of the payload is given by an efficient active and passive detector background shielding, effective not only to prevent the particle background, but also to shield against the diffuse X-ray sky background component falling outside the field of view of the X-ray telescope. These three components are shortly described in the Section 3.

3. The scientific payload

3.1. Optics design, technology and technical challenges

The SIMBOL-X optics module will be based on pseudo-cylindrical monolithic Ni electroformed mirror shells with Wolter I profile, adopting the technology already successfully used for making the gold coated soft X-ray mirrors of the Beppo-SAX [9], XMM-Newton [10] and Jet-X/Swift [11] missions. This approach, developed in the past two decades in Italy by the INAF/IASF-Milano and INAF-Osservatorio Astronomico di Brera in collaboration with the Media Lario Technonology company (www.media-lario.com), is well consolidated. The industrial readiness for production is very high, being a number of equipments (e.g. the lapping and metrology machines for mandrels, the electroforming baths, and the vacuum chambers for the gold coating deposition) already available from past projects, with particular regard to the XMM-Newton mission. The diameter of the outermost mirror shell will be 70 cm (as for the XMM project), which is the maximum size allowed with the present mandrel polishing technology. Just a few modification of the process will be implemented:

- As already mentioned, the SIMBOL-X hard X-rays mirrors will rely on much smaller reflection angles than soft X-ray telescopes and, to maintain an external diameter as large as XMM, it is necessary to make use of a very large focal length (in the 20–30 m range), as allowed by the formation flight architecture. The integration equipments based on optical/UV at present available at Media Lario Technologies can fit a focal length ≤8 m; they therefore need to be refurbished for SIMBOL-X.
- With respect to the baseline of the first SIMBOL-X proposal, the reflecting coating is not longer a Pt single layer reflector, but instead a multilayer mirror coating will be applied. The use of broad-band multilayer reflecting films [12] not only will make possible to rely on a much larger FOV (once provided a small decrease of the focal length from the initial value of 30 m to about 20 m), but also in this way the operative range is extended up to

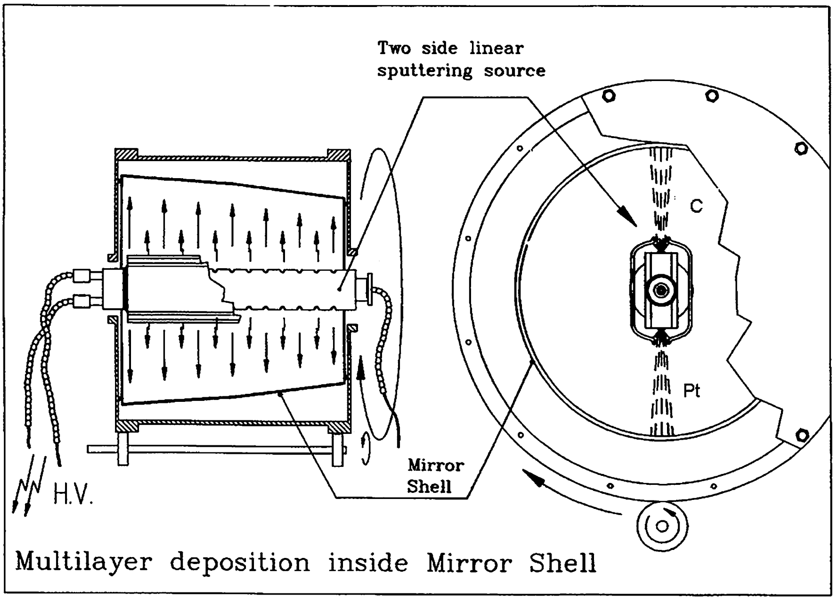

Fig. 2 Scheme of the application procedure by a two-targets DC linear magnetron sputtering source of the multilayer Pt/reflecting coating onto the gold-coated Ni replicated mirror (XMM-like) shells

80 keV and beyond. The multilayer coating will be applied by adding an additional step to the usual process Ni replication process. Once that the gold-coated Ni mirror shell has been replicated from the mandrel, the multilayer mirror will be applied onto the internal surface of the shell by using a two-targets linear DC magnetron sputtering system (see Figure 2), following the approach e.g. developed at the Harvard-Smithsonian Center-for-Astrophysics in the context of the Constellation-X Hard X-ray telescope related activities, that already obtained very promising results [13].

- Due to a need of maintaining the weight as low as possible (under 300 kg, including the two spiders and integration case), the Ni walls will be much thinner (~a factor 2–3) than the XMM mirror shells. At this regard, a new integration procedure (already tested with success [14]) will be implemented with the scope of maintaining good imaging performances, compliant with the top level requirements, also with much thinner and floppy mirror shells. In particular, the new assembly approach is based on the use of two stiffening rings, to be applied at the top and bottom of each shell to restore an acceptable roundness profile and to handle the shells during the integration in the spiders. The two rings will be removed once that the shell is fixed by glue to the two spiders that, in order to maintain a sufficient rigidity, will be based on a number of arms (24) larger than usual.

The final configuration of the SIMBOL-X optics is being addressed in the context of the on-going study Phase A study. The parameters of a particular attractive solution, based on a Focal Length of 20 m, are reported in Table 2. The corresponding expected on-axis effective area is shown in Figure 3.

Table 2 Main parameters of the SIMBOL-X mirror module assuming a focal length of 20 m

Focal length	20 m
Mirror configuration	Wolter I
Coating	Pt/C multilayer
Outer and inner mirror diameter	70–39 cm
Mirror heigh (parabola + hyperbola)	60 cm
Shell material	Ni
Wall thickness (max–min)	0.4–0.2 mm
Expected angular resolution (HPD)	15–20 arcsec
Field of view @ 30 keV (FWHM)	12 arcmin

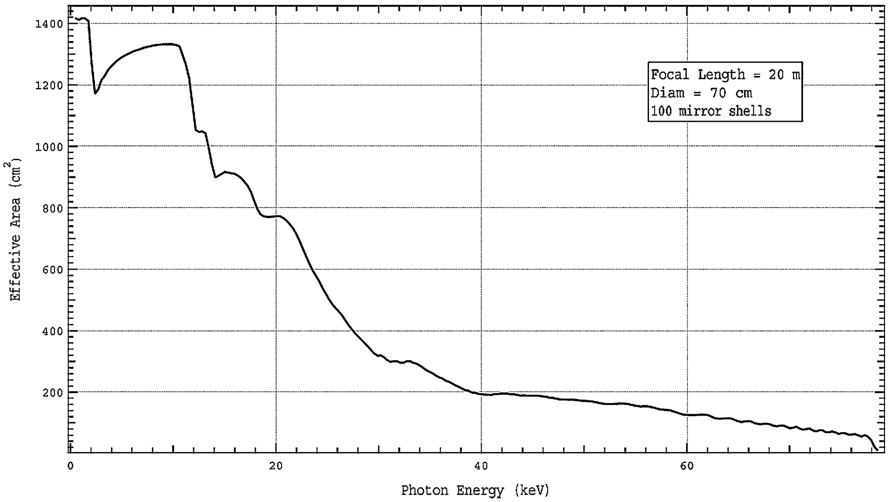

Fig. 3 Theoretical on-axis effective area for the SIMBOL-X optics configuration based on a 20 m focal length whose parameters are reported in Table 2.

3.2. The SIMBOL-X focal plane

The design of the detector assembly will be tightly tailored to the final mission parameters that are being worked out and optimized during the phase A study [15]. At this stage, the present design takes into account the most important parameters for the mission assuming the 20 m focal length optics option. These are shown in Table 3. The above characteristics have led to the design of a two stages focal plane system, operating at a temperature between -30 and $-40\,^{\circ}$C, which will be described in detail in the following. Basically, it is based on a silicon low energy detector on top of a Cd(Zn)Te high energy detector, both surrounded by an active and passive shielding (Figure 4).

The low energy detector (LED) of SIMBOL-X is a Silicon Drift Detector (SDD) with DEPFET (DEPleted Field Effect Transistor) readout [16], also called "Macro Pixel Detector" or "Active Pixel Sensor" (APS). Prototypes of macro pixel detectors have already been developed, built and tested by the semiconductor laboratory of the MPE Institute (Garching, Germany). The LED consists of 128×128 pixels with a baseline size of $500 \times 500\,\mu\text{m}^2$ with $\sim 450\,\mu$m depletion depth. This thick depleted bulk in combination with a thin entrance window results in a high quantum efficiency of the bare detector of already $>85\%$ at 1.0 keV and 95% at 10 keV and still 45% at 20 keV.

Table 3 The focal plane characteristics

Parameter	Value (and origin)
Energy range	<0.5–80 keV
Energy resolution	~130 eV @ 6 keV (Fe line)
	~1 keV @ 68 keV (^{44}Ti line)
Overall size	8 × 8 cm^2 (coverage of 12 arcmin of FOV with 20 m focal length)
Pixel size	~500 × 500 μm^2 (oversampling of 15 arcsec HEW PSF)
Max count rate	~10,000 c/s (observability of a ~1 Crab flux)

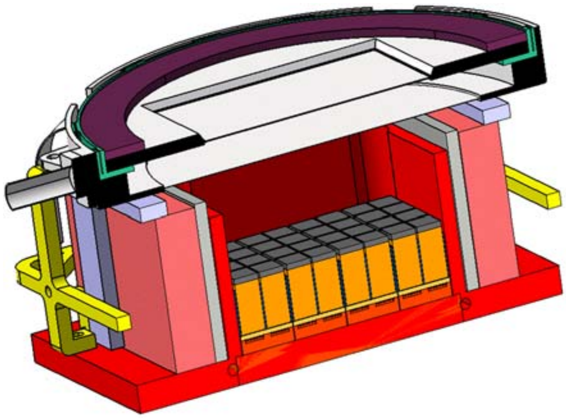

Fig. 4 The SIMBOL-X focal plane, based on a stack of the low energy Si detector on top of the Cd(Zn)Te high energy detector; the whole system is surrounded by an active/passive shielding

The detector is logically and functionally divided into four quadrants of 64 × 64 pixels each. All four quadrants are read-out in parallel at a frame time of 256 μs. This short integration time allows the operation of the detector even at room temperatures with an expected energy resolution of about 500 eV (FWHM). In order to further reduce the noise contribution by leakage currents and to achieve an energy resolution of < 145 eV (FWHM) at 5.9 keV the wafer must be cooled down to only −30 °C (assuming a leakage current of 0.26 nA/cm^2 at room temperature).

The high energy detector (HED) of SIMBOL-X is constructed from a mosaic of several identical cameras, each formed by individual 2 mm thick CdZnTe crystals. The whole detector surface will be ~10 × 10 mm^2 covered with 256 × 256 pixels. As an alternative 0.5 mm thick Schottky barrier CdTe crystal with the same number of pixels. Each crystal is connected to its own read-out electronics, the IDeF-X (Imaging Detector Front-end for X-rays) ASIC developed by CEA/Saclay, forming a complete individual X-ray camera which allows operating in the 5–100 keV range, partly overlapping the low-energy range of the silicon detector. In the current design eight individual X-ray cameras will be merged to form a 2-by-4 module having its own flex for input and output signals. Reliable, radiation tolerant, low power consuming and low-noise read-out electronics in combination with high quality Cd(Zn)Te crystals covered with small pixels are therefore mandatory. The technology for the HED implementation is already pretty advanced and it will be consolidated during the Phase A study.

3.3. Passive and active shielding of the particle and X-ray diffuse background

As there is no telescope tube between the mirror and the focal plane unit in a formation flight configuration, there is a need to protect the detectors from seeing X-rays coming from outside of the mirror, which would otherwise generate an unwanted background [17]. When integrated over even a modest solid angle, the Cosmic Diffuse X-ray Background outside the FOV of the mirror has indeed a level much larger than what is required to reach the desired sensitivity. As a matter of fact, in the case of a 2π opening angle of the detectors on the sky, the sensitivity would be reduced by two orders of magnitude, i.e. the gain in sensitivity brought by the focusing would be entirely lost. In order to stay on reasonable background level as 10^{-4} cts/cm^2/s/keV at 30 keV photon energy, a passive collimator system with an opening angle seen from the detector not larger than 3 deg FWHM should be used. In order to do that, we combine a "sky baffle" placed on the mirror spacecraft around the mirror, and a collimator placed on top of the focal plane. Both the sky "sombrero-like" baffle and the collimator will be graded shields to stop the highest X-ray background energies and to avoid unwanted fluorescence lines. From the phase 0 mission study, we know that we for a complete shielding we should implement a 3 m diameter sky baffle, so that a $\sim$1.5 m collimator is sufficient. The collimator and the "sombrero-like" baffle are both made of a layer of tantalum (with a transmission coefficient of 10^{-4} up to 100 keV), followed by a series of layers of different materials, each able to stop the fluorescence photons by the previous layer although emitting a lower energy X-rays. In the present configuration this multilayer system is made of Ta, Sn, Cu, Al and C. The latter element emits photons of $\sim$0.4 keV, i.e. below the low energy threshold level of SIMBOL-X.

Besides the X-rays entering the detector housing directly, we also need to take into account for the particle background due to the cosmic rays presence hitting the detector spacecraft isotropically. We will therefore make use of an active anticoincidence system in combination with a passive shield surrounding the two focal plane detectors. When charged particles crosses the detector payload, the anticoincidence system triggers simultaneously the detectors and the active shielding. The recorded events are tagged and can be easily removed from the science data. Presently, a very attractive solution to be consolidated during the Phase A study is based on plastic scintillators in combination with a passive shielding made of the same material as the collimator. A second "spare" solution is instead based on classic inorganic scintillators like BGO, NaI or CsI crystals. The former has the advantage that is not only mechanically and electronically easier to realize, with a more reduced weight, but also is not affected by unwanted activation induced background lines close the 30 keV region (which is of high scientific interest because it is where the CXB spectrum peaks), as are instead all the inorganic crystals above mentioned.

4. Performances

In Figure 5 we show the SIMBOL-X flux sensitivity for the optics design configuration, reported in Table 2. The assumed integration time is 1 Ms. As can be seen, the mission will be characterized by an improvement in flux sensitivity over INTEGRAL and SAX-PDS by at least two orders of magnitude below $\sim$80 keV. In Table 4 we report the number of CXB sources resolved in the 20–40 keV energy interval (i.e. where there is the peak of the spectrum) for a single pointing and an observation time of 1 Msec for the SIMBOL-X configuration reported in the present paper, for the past SIMBOL-X design, and for the NUSTAR and NEXT missions. At this regards, this evaluation has performed by using the

Table 4 Capability forpast and present SIMBOL-X configurations and other hard X-ray missions to resolve the Cosmic X-ray Background in the 20–40 energy region assuming 10^6 s of observing time

Project	HPD	FOV	$F_{\rm lim}$ μCrab	%CXB	Sources/FOV$_{\rm FWHM}$
• NuStar	40″	15″	0.8	40%	15
• NeXT	30″	12″	0.7	50%	12
• Simbol-X (old design)	30″	7′	1.4	35%	2
• Simbol-X ML	15″	12′	0.5–0.7	65%	25

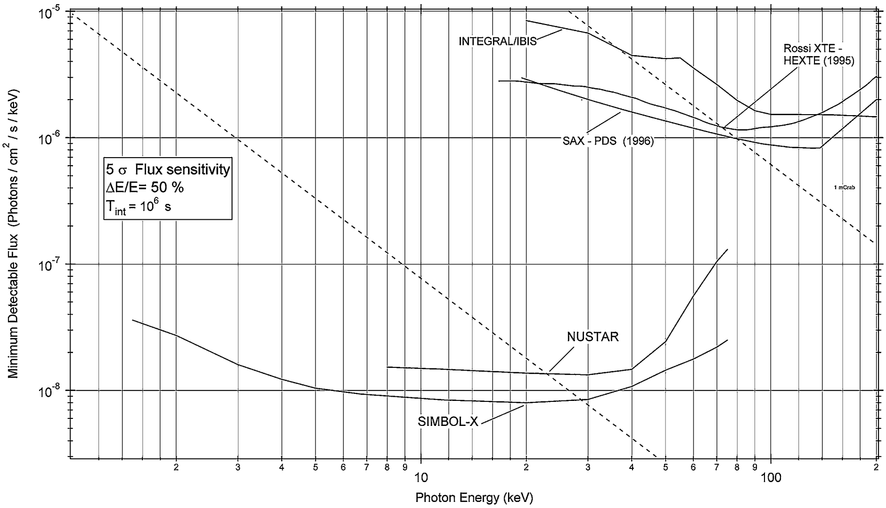

Fig. 5 Continuum on-axis sensitivity of SIMBOL-X for the options based on 20 m focal length and 70 cm external mirror (see parameters reported in Table 2). The sensitivity is calculated with the assumption of an internal background of 10^{-4} cts/s/cm^2/keV, 1 Ms of observation and $\Delta E = E/2$. For a better comparison the flux sensitivities of INTEGRAL/IBIS, ROSSI/XTE/HXT and SAX-PDS also plotted in this figure. Finally also the expected NUSTAR performance is reported assuming the same integration time and background level as SIMBOL-X

logN/logS behaviour expected from the Comastri model for the Cosmic X-ray Background. As can be seen, with the new SIMBOL-X configuration about the 65 % of the CXB will be resolved, with a performances better than the other missions used for comparison.

5. Conclusions

We have presented the main characteristics of the SIMBOL-X mission, a formation flight hard X ray telescope project being jointly studied by CNES and ASI, with a large participation of the French and Italian scientific communities (led by the CEA and INAF Institutions respectively). The MPE and IAAT German Institutes will also take part in the project. Thanks to the use of a long focal length, allowed by the formation flight configuration, and to the use of multilayer coated mirrors, it will be enabled the use of focusing optics in the hard X-ray region (10–100 keV), with an enormous gain in flux sensitivity and angular resolution compared past unfocused missions. The use of a combined focal plane, formed by a stack of a Si-based and a Cd(Zn)Te-based soft and hard X-ray detectors will allow to cover a very large X-ray band, ranging from 0.5 keV up to 100 keV. An active/passive shield system will be implemented to guarantee an instrumental background level as low as possible. The joint Phase A study will end in middle 2007, while the launch is foreseen by the 2013 year.

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