SIMBOL–X : a new generation X–ray telescope in the 0.5–70 keV range

Philippe FERRANDO[1]

Service d'Astrophysique, CEA/Saclay, 91191 GIF-sur-YVETTE, Cedex
e-mail : pferrando@cea.fr

ABSTRACT – *SIMBOL–X is a high energy "mini" satellite class mission which is proposed to CNES, by a multi-lateral collaboration, for a launch before the end of this decade. SIMBOL–X is making use of a classical X–ray mirror, of ~ 600 cm^2 maximum effective area, with a 30 m focal length in order to cover energies up to several tens of keV. This focal length will be achieved through the use of two spacecrafts in a formation flying configuration. This will give to SIMBOL–X an unprecedented spatial resolution (20 arcsec HEW) and sensitivity in the hard X–ray domain. By its coverage, from 0.5 to 70 keV, and sensitivity, SIMBOL–X will allow major breakthroughs in the study of non thermal astrophysical processes, in both compacts and extended sources. Prime targets for SIMBOL–X are sites of particle acceleration, in particular those related to the accretion onto black holes.*

In this paper, we first summarize the scientific context and goals for this mission. We then describe the mission concept, with the baseline mirror and focal plane systems and give detailed estimates of the expected performances in terms of sensitivity. The requirements on the station keeping between the two spacecrafts and the current status of the mission are finally given.

1 – Introduction

Because the Earth atmosphere is completely opaque to X–ray radiation, i.e. to photons with energy above ~ 100 eV, X–ray astronomy is a science which has to be carried out with instruments on satellites. This science is thus relatively young, and is still growing. By looking at the sky in X–rays, astrophysicists are studying objects which are either heated at very high temperatures, typically between 1 and 100 MK, as for example the gas inside cluster of galaxies and the matter shocked by supernovae explosions, or which correspond to non-thermal processes. Signature of such processes are for example the synchrotron emission of particles accelerated close to very dense objects as black-holes (with stellar masses in binary systems, or very massive black holes at the centre of Active Galactic Nuclei) and the inverse Compton emission generated in very hot plasmas found in the vicinity of the same objects.

This is well beyond the scope of this paper to go into the description of the extremely rich field of X–ray astrophysics, as well as into the list of all the fundamental questions that can be adressed through X–ray observations. For these questions, we refer the interested reader to the excellent review of Charles & Seward [1]. It is sufficient here to first mention that, similarly to what happens at other wavelengths, the interpretation of X–ray emission from astrophysical objects relies on the detailed spectral information, and on the morphology of the emission : the spectral shape and the

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[1] This paper is presented on behalf of the SIMBOL-X collaboration, which comprizes members from CEA/Saclay (France), Observatory of Brera (Italy), Observatoire de Meudon (France), Observatoire de Grenoble (France), and Leicester University (UK).

presence of emission lines carry informations on the physical state of the emitting plasma (density, temperature, state of ionisation, thermal versus non-thermal emission process), whereas the morphology of the emission allows deep insights into the physics of the objects studied, either by itself or by comparison with observations at other wavelengths. Second, it is important to note that for a number of fundamental X–ray emitters, like type 2 Active Galactic Nuclei and star forming regions, the low energy X–ray emission is absorbed within the material of or close to the source of the emission itself, so that these sources can be detected and studied in X–rays above several keV only. For these reasons, planned X–ray instruments are now required to have “good” angular and spectral resolutions, and are looking into extending their energy range beyond the usual “few keV” limit that is discussed below.

1.1 – X–ray astrophysics imaging techniques below 10 keV

One difficulty of X–ray instrumentation is that X–ray photons cannot be focussed as lower wavelength ones, since they are absorbed by matter under normal incidence conditions. Reflection on a surface can occur only under grazing incidence angles, the cut-off angle decreasing when the energy increases. This has been the major problem in building X–ray telescopes, and is the reason why X–ray instruments imaging characteristics look poor compared to optical astronomy. Below ~ 10 keV, astrophysics missions are flying with focussing X–ray mirrors built on this grazing incidence reflection property. The most important ones operating today are the Chandra american mission, and the XMM–Newton ESA mission. They both use a Wolter I combination of parabolic and hyperbolic surfaces [2], which guarantees the minimum focal length for a given aperture and allows to nest together many confocal mirror shells. The largest collecting area is achieved by the XMM–Newton observatory [3] by combining 3 X–ray mirror systems of 58 reflecting shells each ; it thus reaches ~ 0.45 m^2, to be compared with the now common 50 m^2 collecting area of optical observatories. Fig. 1 shows one of the XMM–Newton mirrors together with the Wolter I design principle. The quality of the image, as measured by the so called Half Energy Width (HEW, circle containing half of the photons coming from a point source), is also poorer than in the optical ; for example, each of the XMM–Newton telescopes has a 15 arcsec HEW. The current angular resolution record in X–rays is that of Chandra [4], with 0.5 arc seconds, reached at the expense of the collecting area, 5 times less than XMM–Newton.

Whereas very successful, these optics are in practice limited to a maximum energy which is proportional to the focal length of the mirrors. With focal length of 7.5 and 10 metres resp. XMM–Newton and Chandra telescopes are at the limit of what can be accomodated in a launcher shroud, and have a high energy limit of about 10 keV.

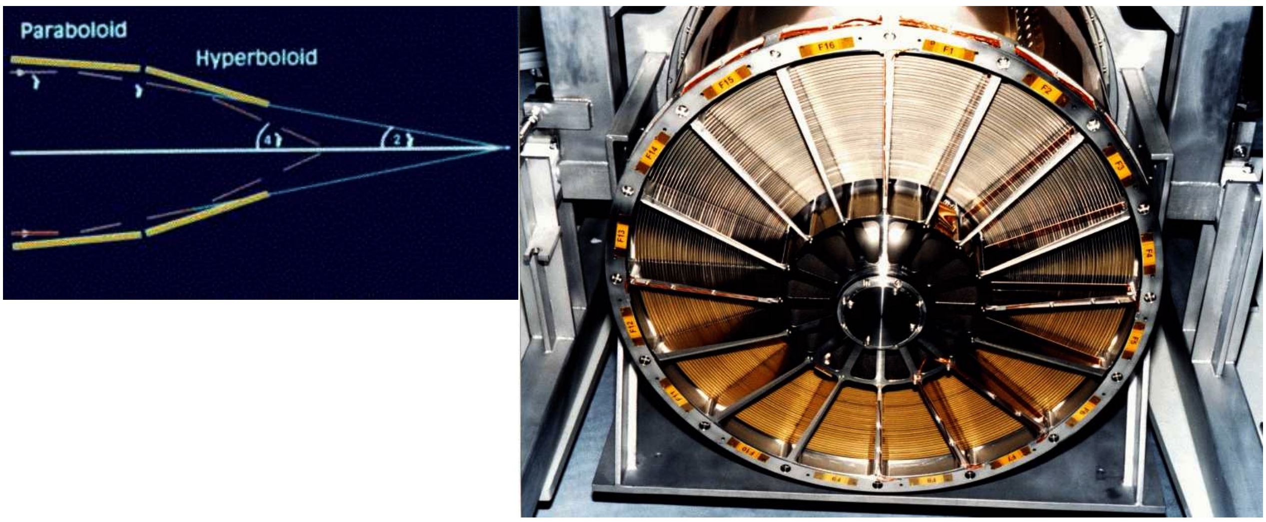


Fig. 1 : *Left* : Wolter I focussing optics principle. *Right* : one of the XMM–Newton mirrors ; it has 58 confocal shells for an outside diameter of ~ 70 cm.

1.2 – X–ray astrophysics imaging techniques above 10 keV

Because of the above mentionned limitation of X–ray focussing optics "hard X–ray" astronomy has been relying on two other techniques. One is the use of a simple collimator to select a part of the sky, with photons detected by a non imaging detector system. This is the case for example of the HEXTE instrument on RXTE, which has a collimator aperture of one square degree. The other technique uses a coded mask, which for each point source in the sky projects an unambiguous pattern onto an imaging detector system [5]. The sky image is reconstructed by unfolding the mask motives from the image measured by the detector. This technique, which allows to reach angular resolutions of ~ 5–15 arcminutes, is employed in the INTEGRAL mission launched in October 2002.

Besides their very poor angular resolution, both techniques suffer from the fact that the detecting area is equal to (or even larger than for coded masks) the collecting area. This first conducts to very bulky and expensive detector systems for matching the needs of large collecting areas. More importantly, this results in a very large instrumental background compared to focussing systems. This background is indeed proportional to the effective detection area for a celestial point source, which is the full detector for a coded mask system, whereas it is only about the HEW size with a mirror system. Another drawback is the extreme difficulty of studying diffuse emission on large angular scales.

1.3 –Bridging the gap with SIMBOL–X

The transition of techniques around 10 keV which has been outlined above results in roughly 2 orders of magnitude differences in instrument characteristics (angular resolution and sensitivity) between the "X–ray" and "γ–ray" domains. This unfortunately happens roughly at the energy above which the identification of a non thermal component is unambiguous with respect to thermal emission. Seen from the low energy side, this strongly limits the interpretation of the high quality X–ray measurements, and particularly that related to the acceleration of particles ; seen from the high energy side this prevents the identification and thus the study of hard X–rays emitters in crowded fields or complex systems, as e.g. those involving jets.

With the SIMBOL–X mission we propose to extend the use of the X–ray focussing technique up to ~ 70 keV, i.e. well beyond the transition between thermal and non thermal emissions in astrophysical systems. Offering a constant spatial resolution and a "soft X–ray type" sensitivity over the full energy range from 0.5 to 70 keV, SIMBOL–X will be an excellent instrument to elucidate the origin of the non thermal emission in accretion / acceleration astrophysical sites, both compact and extended.

SIMBOL–X concept is very classical, in the sense that is uses a Wolter I optics focussing X–rays onto a focal plane detector system, as in the successful Chandra or XMM–Newton missions. Its originality lies in the focal length of its mirror which is brought to 30 metres, allowing the large increase of maximum energy that can be detected compared to previous missions. In order to accomodate such a long focal length, which cannot fit in a single spacecraft, we propose to take advantage of the upcoming formation flying technology, by flying the mirror and the detector systems on two separate spacecrafts, as sketched on Fig. 2.

In the following of this paper we first give the main characteristics of SIMBOL–X together with its scientific objectives. We then describe the present baseline for the mirror and detector systems, the expected detector background, and the resulting SIMBOL–X sensitivity. We finish with the requirements on station keeping, and with the mission status today. As will be shown, apart for the new formation flying technique for which SIMBOL–X requirements are well within what is currently studied in other contexts, SIMBOL–X does not rely on any technological breakthrough. We therefore propose to launch it before the end of the decade. This would not only ensure a unique scientific return, but this would also be an excellent preparation, from both scientific and technical points of view, to the large observatories which are planned in the next decade.

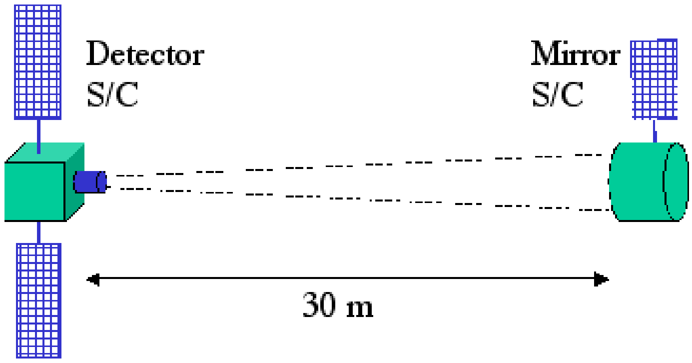


Fig. 2 : in-flight SIMBOL–X configuration : the X–ray optics is carried by one spacecraft, and concentrates the X–rays on focal plane detectors carried by a second spacecraft.

2 – Scientific goals

The main characteristics of SIMBOL–X are summarized in Table 1. The most outstanding are its unique angular resoution and sensitivity above 10 keV, which will specifically allow to :

- determine the origin of the hot component at the center of our Galaxy,
- determine the physics of the accretion process onto Sgr A*, the 2.6 million solar masses black hole at the centre of our Galaxy,
- localize and study the acceleration sites in supernovae remnants,
- determine the origin of the high energy emission in clusters of galaxies,
- elucidate the high energy emission mechanism in the jets of quasars and microquasars,
- constrain the models of high energy emission in Active Galactic Nuclei,
- elucidate the nature of the diffuse X–ray background,
- study the accretion process in binary systems, especially those with a quiescent black hole,
- study the particle acceleration around magnetically active stars.

Table 1 : SIMBOL–X main characteristics

Parameter	Value	Comment
Energy range	0.5 – 70 keV	
Effective area	600 cm^2	value up to ~ 35 keV, 150 cm^2 @ 50 keV 10 cm^2 @ 67 keV
Angular resolution	20 arcsec	Half Energy Width
Field of view	6 arcmin	@ 50 % vignetting
Energy resolution	120 eV @ 6.4 keV 2 % for E > 15 keV	CCD type detector CdZnTe detector
Point source sensitivity	< 5 10^{-8} ph/cm^2/s/keV	@ 30 keV, for a 5 σ detection in 100 ks, and with $\Delta E/E$ = 50 %

In most of these subjects detailed simulations have been made of SIMBOL–X observations, with the mirror and detector characteristics mentionned below, and by taking into account realistic source fluxes and background estimate. Lacking of space, we will simply mention here two examples to illustrate the SIMBOL–X sensitivity. On the supernovae remnant side, a detailed map of Cas A above 20 keV can be done in 100 ksec, and a significant spectral measurement of its brightest 1 arcmin^2 part can be obtained up to 50 keV. On the AGN jet side, the spectrum of the Pictor A hot spot at 4 arcmin from the nucleus (well isolated with SIMBOL–X optics) can be significantly measured up to 40 keV in 50 ks of observation. None of these measurements can be performed by any existing instrument today.

3 – Instrument design and performances

As mentionned in Sect. 1, SIMBOL–X instrumentation is shared between the optics, carried by one satellite, and the focal plane detector, carried by a second satellite which is maintained at a constant distance (and with a constant orientation) from the first one. We detail here the baseline design for these two parts of the telescope.

3.1 – The optics

The optics is based on the successful Wolter I design, which has been discussed in Sect. 1.1. Building on the experience acquired on Beppo–SAX, Jet–X, SWIFT, ABRIXAS and XMM–Newton mirrors, the mirrors will be made following the Nickel electroforming replication method (e.g. [6]). This offers the advantage to provide high throughput optics with very good imaging performances. Shortly, in this technique the reflecting material is deposited first onto a superpolished mandrel with the adequate profile ; the mandrel with its coating is then put into an electrolytic bath in which the Ni shell is electrodeposited onto the reflecting material ; the mirror is finally separated from the mandrel by cooling of the whole structure.

The baseline design for SIMBOL–X is to have a 108 shells mirror, with an outer diameter of 70 cm (like one XMM–Newton module), and an angular resolution of 20 arcseconds of Half-Energy-Width. The coating will be Pt, in order to increase the high energy response w.r.t. a more classical Au coating. The focal length will be 30 metres. Figure 3 shows the effective area as a function of energy, for the baseline design. It is over 600 cm^2 at low energy and has roughly a constant value up to about 35 keV, before starting to decrease and fall below one cm^2 above more than 70 keV. The field of view (FOV) will be of 6 arcminutes at 50 % vignetting. On the same figure is shown for comparison the effective area of one XMM–Newton mirror, the largest throughput optics built up to date. The gain given by SIMBOL–X optics, which has a HEW equivalent to that of the XMM–Newton (~ 15 arcsec), is obvious.

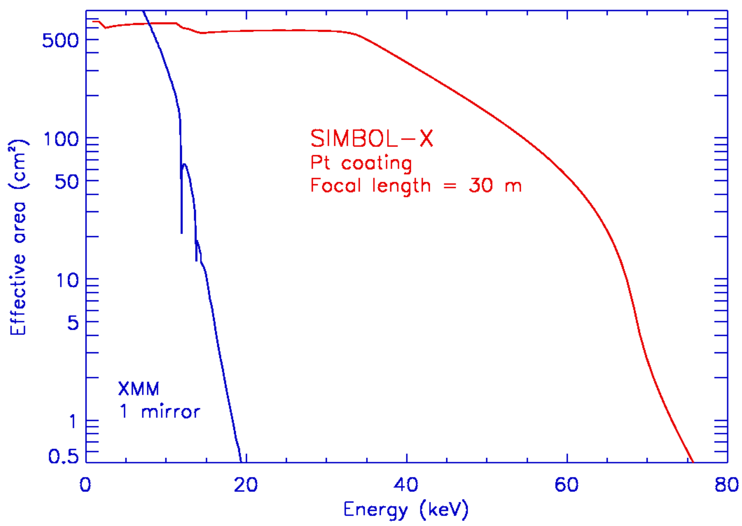


Fig. 3 : Mirror effective area for the baseline SIMBOL–X configuration (see text). The maximum value is ~ 650 cm^2 below 10 keV. The effective area of one XMM–Newton mirror is given for comparison.

The mirror shells weight will depend on the compromise that will be done between weight and stiffness, and thus quality, of the optics. A first estimate, with no optimisation effort, gives a mirror weight of about 160 kg. The final weight which will also include the mechanical structure as well as baffles should be well within a mini-satellite weight budget.

Finally, the Brera Astronomical Observatory is presently working on two technologies that may replace the present baseline of Pt coating on Ni shells. The first is the development of multilayer optics which allows to enhance the effective area by large factors on the high energy side. The second is the use of ceramic materials, in particular SiC, instead of Ni which allows to build much lighter optics [7]. These options will be considered for the final design of the SIMBOL–X optics.

3.2 – Focal plane detectors

The focal plane detector system has obviously to be a spectro-imager covering the full Field Of View with a pixel size well below the Half Energy Width of mirror Point Spread Function. With a focal length of 30 m, the FOV of 6 arcmin converts into a minimum detector diameter of 5.2 cm, whereas the Half Energy Width of 20 arcsec converts into a focal spot of 2.9 mm. Allowing for about 1 cm of jitter in the focal plane localization with respect to the optical axis, and for an oversampling of the PSF by a factor of 4 (as that of the EPIC/PN camera onboard XMM–Newton, [8]), this sets the following spatial requirements on the detector system :

focal plane detector diameter	:	6 cm minimum
pixel size	:	750 microns maximum

If SIMBOL–X major improvement will be the discovery and study of sources above 10 keV, the understanding of the physics of these sources will not be possible without the measurement of their spectra also down to 0.5 keV or less. This will for example be crucial to correlate the thermal versus non thermal emission in these sources, and to measure the column density towards them. Moreover, there are below 10 keV a number of important X–ray lines, particularly that of Iron, which are very powerful diagnostics in the compact objects that are prime SIMBOL–X objectives. Since a lot of these sources are highly variable, the only way to guarantee the simultaneous measurements of both low and high energy X–rays is to cover the full 0.5–70 keV range with SIMBOL–X instruments.

We thus require below 10 keV a detector system with an energy resolution sufficiently good to provide i) reasonable measurements of the Iron line and ii) a good coverage of the energy range below 1 keV. Above 10 keV, we require a detector system which makes the maximum use of the mirror area, with a less stringent requirement on the spectral resolution.

These constraints cannot be filled today by a single detector, so that our baseline focal plane design combines an array of CCD detectors directly on top of an array of CdZnTe pixellated detectors. This is completed by an active anticoincidence shield to reduce the background level in the CdZnTe, and by an optical blocking filter in front of the camera. Photons of energy less than ~15 keV will stop in the CCDs, whereas higher energy photons will go through the CCDs to be detected in the CdZnTe array. A sketch of the detector configuration is given in Fig. 4 left.

The design of the focal plane is obviously not finalized at this stage, but we want to stress that our baseline configuration is based on detector systems which do not require heavy technological development. Obviously the operation of CCDs in space is presently demonstrated by the Chandra and XMM–Newton missions. The newer CdZnTe detectors are similarly under active study, with prototype detectors with their electronic chain tested in laboratories or in balloon flights (e.g. [9, 10, 11]). It is also worth noting that this CCD-CdZnTe combination is also envisionned in the context of other future missions, like NeXT or XEUS (e.g. [12]).

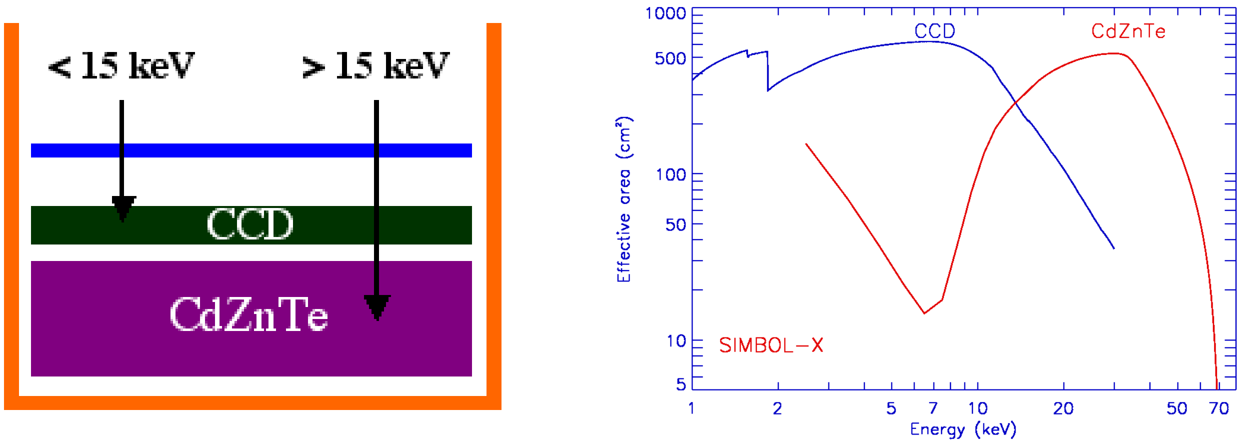


Fig. 4 : *Left* : sketch of the SIMBOL–X detector configuration. X–rays coming from the mirrors will first cross an optical blocking filter, and will then be detected either in the CCD or in the pixellated CdZnTe below, depending on their energy. *Right* : the overall on axis effective area of SIMBOL–X, combining mirror area, filter transmission, CCD transparency and detector quantum efficiencies.

The CCD baseline for SIMBOL–X is an array of front illuminated frame transfer devices with 250 µm depletion depth for a thickness of 300 µm. The cooling to the operating temperature of ~ – 100 °C will be done by bonding the store-section of the CCD onto a Thermo Electric Cooler (TEC). SIMBOL–X will combine 4 CCDS with a ~ 3 cm large imaging section to make-up the 6 cm diameter FOV. The store section, with its attached thick cooler, will thus be completely out of the FOV. This will ensure that no thick inactive material will be located in the FOV between the CCDs and the CdZnTe detectors. Such devices, with their cooler, are currently under test in Leicester University.

Pixellated CdZnTe detectors are now the baseline of a number of hard X–ray and γ–ray projects. They have the advantage of offering a far better energy resolution and spatial resolution than scintillator detectors, and to operate at room temperature (e.g. [13]). The use of a segmented anode allows to define small size pixels in a single crystal. We are currently testing in CEA/SAp $10 \times 10 \times 2$ mm^3 devices from eV-Products, with 8×8 pixels surrounded by a guard ring. The 2 mm thickness ensures a 100 % photon absorption up to ~ 80 keV. The read out of each chip, comprising a complete pulse-height analysis for each pixel, will be achieved by a dedicated ASIC below each of the crystal. For that we will build on the experience gained in CEA/SAp when designed and building the ISGRI CdTe imager of the IBIS instrument on INTEGRAL. The focal plane will be made by assembling the necessary number of crystals and their associated electronics, this exact number depending upon the size of the single crystal that will be finally chosen. We envision to have 3 cm wide, 2 mm thick, crystals, with 500 µm wide pixels.

Finally, the optical blocking filter will be derived from, if not similar to, the medium filter in the XMM–Newton EPIC cameras [14], whereas the active shielding will be either a plastic scintillator or a BGO crystal (as e.g. in [9]).

If the necessity to have a low and high energy detector is clear, the details of the detector system are not fixed yet. The configuration given above describes one realistic possibility. Other alternatives, like e.g. the use of DEPFET based Active Pixel Sensors [12] working at room temperature instead of CCDs, will be envisionned during the phase A study.

3.3 – Background and sensitivity calculation

In order to estimate to sensitivity of SIMBOL–X, we have used the background spectra studied in the context of Constellation–X. This mission is designed for an L2 orbit, as SIMBOL–X, and has an actively shielded CdZnTe detector, as SIMBOL–X. Ramsey [10] has published a detailed analysis of the detector background spectrum, reproduced in Fig. 5 left. As shown, this spectrum is made a diffuse sky component and of an internal instrumental background.

The SIMBOL–X background spectrum was calculated by adding the Constellation–X internal background to the diffuse sky component, from [15], correctly scaled to the relevant SIMBOL–X parameters (effective area, and required extraction region). The result is shown in Fig. 5 right for a 1 arcmin diameter region of the sky.

With this background spectrum, we have then calculated the SIMBOL–X sensitivity for detecting point sources with a required signal to noise ratio, following the formula :

$$S/N = f \times A \times [\ \Delta E \times T / B\ ]^{1/2}$$

with S/N being the signal to noise ratio, f the source flux (cts/keV/cm^2/s), A the effective detection area (cm^2), ΔE the energy range of integration for flux and background (keV), T the exposure time (s), and B the background spectrum in the integration detector area (cts/s/keV) as given in Fig. 5.

The resulting sensitivity curve for a point source detection at the 5 σ level, in 100 ks of observing time, is given in Fig. 6 in comparison with other instruments. We have assumed an extraction region of 1 arcmin diameter for the source photons, i.e. three times the HEW of the PSF. This sensitivity curve also describes the sensitivity of SIMBOL–X to diffuse emission on the scale of 1 arcmin diameter. As expected for an X–ray focussing telescope, the SIMBOL–X sensitivity curve has roughly the shape of the XMM–Newton and Chandra curves (which have no diffuse component here), but is displaced by about a decade in energy. SIMBOL–X is about 100 times better than existing instruments in the 10 to 35 keV range, and has a sensitivity equivalent to INTEGRAL/IBIS at ~ 70 keV.

3.4 – Requirements on spacecrafts, station keeping, and telemetry

Whereas detailed mass and electrical consumption estimates are not yet made, we can safely anticipate that both the mirror and the detector systems will fit within the approximate enveloppe of 300 kg, 300 W of the “mini-satellite” class. Depending on the exact technology chosen, especially for the low energy detector, the detector system might fit into the enveloppe of a micro-satellite system but this remains to be demonstrated. At this stage the SIMBOL–X baseline is to have two mini-satellite class spacecrafts. For allowing uninterrupted observations of variable sources, as well as minimising the differential gravity forces between the two spacecrafts, SIMBOL–X will be put in in orbit around the L2 Lagrangian point.

To keep a constant image quality requires the following constraints on the spacecraft relative positionning :

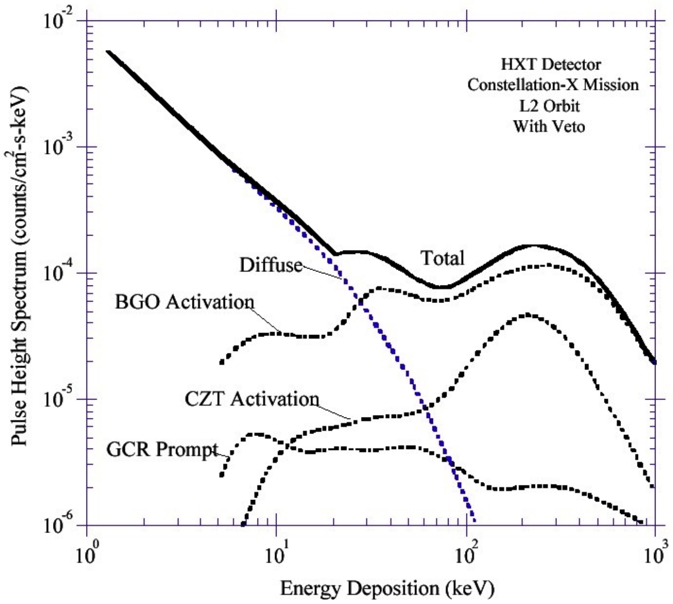
• their distance must be kept constant within 1 cm, i.e. a fraction of the anticipated few cm focal depth. This is to avoid image distortions. No monitoring of that distance is necessary for the scientific point of view.

• their positionning perpendicular to the optical axis must be kept within 1 cm, in order to always keep the full FOV inside the detector area. If larger values can in principle be accomodated at the expense of enlarging the detector size, the 1 cm value we quote seems a reasonable compromise. This position has to be constantly monitored within 0.5 mm, so that the sky position of each detected photon can be reconstructed whatever the relative movements of the two spacecrafts.

• the mirror axis must stay perpendicular to the focal plane within 1 arcmin, with a monitoring of this angle within 3 arcsec. This is to minimize efficiency variations due to the telescope vignetting for off-axis viewing angles.

Given the high energy fluxes, typical SIMBOL–X observing times on the same target will be of the order of 100 ks. The change of astrophysical source, i.e. of absolute position of the two spacecrafts with respect to the celestial coordinates will thus be made at the rate of roughly one per day.

Finally, we are requesting a scientific telemetry bit rate of 48 kbits/second. This will allow to transmit all photons detected by both detectors for a source with a 1 Crab intensity (50 cts/s in the CdZnTe, 400 cts/s in the CCD, with ~ 100 bits/s per photon as in the EPIC cameras on XMM–Newton).



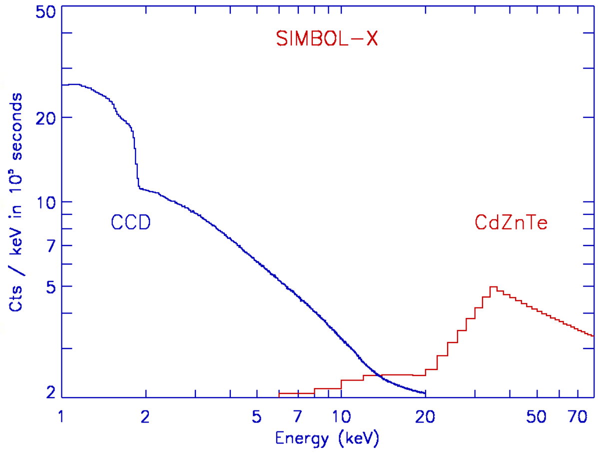


Fig. 5 : *Left* : background spectrum of 1 cm^2 of the Hard X-ray Telescope detector of Constellation X, from [10]. *Right* : background spectrum in 100 ks of observation for a 1 arcmin diameter region for the two detectors of SIMBOL–X.

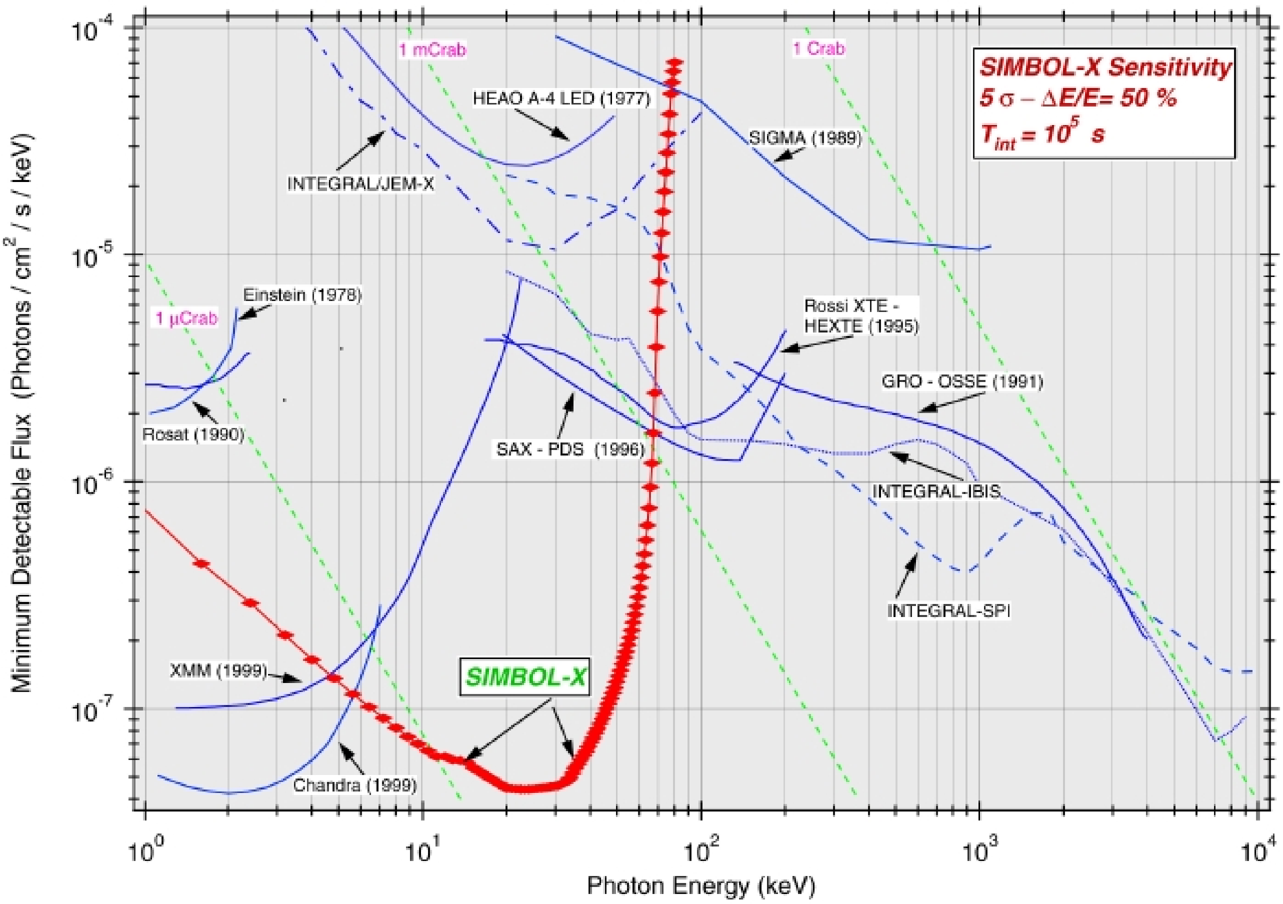


Fig. 6 : sensitivity curve for point source detection for SIMBOL–X compared to past and present X– and γ– ray missions. For SIMBOL–X this curve is also the sensitivity to diffuse emission on angular scales of 1 arcmin. See text for details.

4 – Collaboration, status and schedule

The SIMBOL–X mission is a collaboration involving France (CEA/Saclay, PI Institute, and the Grenoble and Meudon observatories), Italy with Brera Observatory, and United Kingdom with Leicester University. At this early stage, the participation of each country which has still to be secured is envisionned to be the following. France will build the detector spacecraft, the high energy part of the focal plane detector, and will take care of the formation flying aspects. Italy is in charge of building the mirror and the mirror spacecraft. United Kingdom is in charge of the CCD part of the focal plane. The collaboration of other institutes is envisionned, with the constraint that the number of interfaces has to stay minimum in order to keep the project as simple as possible.

SIMBOL–X has been presented to the Astrophysics group of CNES during the first semester of 2002, in the context of the CNES “Séminaire de prospective”, with a proposed launch date in 2009. This group has selected SIMBOL–X in June 2002 for beginning a phase A study.

As apart the new formation flying aspects SIMBOL–X does not require any technological breakthrough, this mission can indeed been developped on the relatively short timescale which has been proposed. Launching SIMBOL–X before the end of the decade would indeed provide an excellent preparation for the large astrophysics missions that are envisionned well after 2010, as Constellation–X and XEUS. Scientifically, SIMBOL–X will be the first to image and study non thermal sources with X–ray sensitivity ; this is bound to result in discoveries which will position extremely well the SIMBOL–X scientific teams for the follow-up of these discoveries by the large observatories when they exist. Technically, SIMBOL–X can demonstrate with actual observing conditions the power of formation flying for high energy optics, as well as the use of the combination of CCD and CdZnTe detectors. This will also position extremely well the involved teams in the hardware side of the future instruments for observatories like XEUS.

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