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The HEXIT-SAT and SIMBOL-X Hard X-ray missions

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Abstract. HEXIT-SAT and SIMBOL-X are two astronomy mission concepts based on hard X-ray ($E \geq 10$ keV) focusing optics, with several Italian researchers involved in the design and definition of both satellites. HEXIT-SAT is based on 4 optics modules with 8 m focal lenghth, each formed by a number of confocal multilayer-coated Wolter I shells, the maximum diameter being 35 cm. Due to their broad-band reflection response, multilayer mirrors allow us to focus X-ray photons with energies beyond 10 keV up to about 100 keV, a region where just direct-view detectors have been operated so far. The SIMBOL-X project instead relies on a single-module optics with 60 cm diameter, and it is characterized by a very large focal length (30 m), achieved by means of two separate spacecrafts (one for the mirror module, the other for the detector unit) in a formation-flight configuration. At the moment the reflecting coating assumed for the mirrors is a Pt single layer film that, due to the very small reflection angles involved, is able to guarantee a high effective area for hard X-rays up to 50 keV. The use of multilayer mirrors to further extend the reflection band is currently being considered. HEXIT-SAT and SIMBOL-X are both characterized by an unprecedented flux sensitivity (with a gain of several hundreds compared to the hard X-ray missions already flown) and a much better angular resolution. In this paper a short review of the main features of both missions is reported.

Key words. Hard X-ray telescopes - multilayer coated mirrors - X-ray astronomical instrumentation

1. Introduction

In the second half of the nineties a hard X-ray experiment with unprecedented flux sensitivity in the 20-300 keV energy band was put in orbit, the PDS system (Frontera et al. 1997) onboard the BeppoSAX satellite (Boella et al. 1997). The observations carried out with this passively collimated detector opened new frontiers in galactic and extragalactic high-energy astrophysics. However, due to its large Field-of-View (FOV, about 1 degree diameter) and lack of angular resolution, the experiment was still limited by a very high intrinsic background and source confusion (the minimum detectable flux was about 1 mCrab at 30 keV in 10^5 s of observation time). Thus, despite the excellent work performed with this experiment, a number of fundamental questions remained open. More recently another large-size hard X-ray experiment, IBIS (Ubertini et al. 2003) aboard the European mission INTEGRAL, was launched and it is still operational. In this case the detector is not narrowly collimated, but it is equipped with a coded-mask system, able to provide a moderate improvement in angular resolution (12 arcmin FWHM). The flux sensitivity is however worse than PDS, because of the much larger FOV (30 deg × 30 deg), which determines a large increase of the background count-rate. Thus, a real breakthrough in hard X-ray astronomy can only be achieved with experiments based on focusing optics with enhanced imaging capabilities. HEXIT-SAT (*High Energy X-ray Imaging Telescope Satellite*) and SIMBOL-X are two astronomy missions based on hard X-ray focusing optics. Many Italian researchers are giving important contributions in the design and definition of both satellites. Exploiting the dramatic improvements in terms of flux sensitivity and angular resolution allowed by the use of concentration techniques, a number of important open questions concerning high energy astrophysics and cosmology could be resolved by their implementation, such e.g.:

- the origin of the Cosmic X-Ray Background (and the real connection between Seyfert 1 and 2 galaxies) by deep observations of selected sky regions at photon energies around 30 keV (see the review on this topic contained in Fiore et al. 2004)
- the behavior of the supermassive Black Hole at the center of our Galaxy (Goldwurm et al. 2003)
- the ^{44}Ti ejecta in Supernova Remnants (Vink et al. 1999);

In the following sections the ideas that have driven the design of the two missions will be discussed, and their main parameters reported.

2. Strategies for the design of a hard X-ray mission based on focusing optics

While in the classical X-ray region (0.1 - 10 keV) a number of missions based on focusing optics exploiting the phenomenon of total reflection at grazing angles have been operated (Einstein, Rosat, ASCA, Beppo-SAX, XMM-Newton and Chandra), so far it was not possible to apply this technical approach in the hard X-ray region and just direct view detectors have been operated. Total reflection occurs for glancing angles below a threshold value α_c, the so called *critical angle*, which linearly depends on the square root of the reflecting material density ρ, and on the inverse of the photon energy E. The effective area of given telescope based on Wolter I optics is approximately (de Korte 1988):

$$A_{eff} \propto FL^2 \times \alpha_c^2 \times R^2 \qquad (1)$$

where FL is the focal length and R is the mirror reflectivity. On the other hand, at energies larger than 10 keV, the cut-off angle α_c becomes very small. Therefore the effective areas achievable with usual focal lengths (FL ≤ 8 m) are almost negligible. For example, even for a high density material like Platinum (ρ = 21.4 g/cm^3), at 30 keV α_c is $\simeq 0.15$ deg while, for comparison, at 5 keV its value is much larger, $\simeq 0.8$ deg. Nevertheless, important technological developments are currently on going, that would make possible in near future the implementation of focusing techniques also beyond 10 keV. In particular, the possibility of flying missions employing the so called *formation flight* configuration will allow us to operate optics with much larger focal lengths. This will be obtained by hosting the focal plane detectors and the mirror modules onto two separate satellites, located to a reciprocal distance of several tens of meters, and being kept aligned to each-other by means of a laser tracking system. In addition, relying on technological efforts achieved in the last decade in thin film technology, the use of wide-band multilayer reflectors based on Bragg diffraction would increase the reflection angles of about a factor 3 with respect to classical single-layer X-ray mirrors. These are the basic principles exploited for the design the focusing systems employed in SIMBOL-X and HEXIT-SAT.

3. The HEXIT-SAT mission

The HEXIT-SAT design has been carried out by a group of Italian scientists and engineers with the specific aim of tailoring the mission performances to resolve in the hard X-ray region the celestial objects giving rise to the X-ray Cosmic Background (Fiore et al. 2004). In addition, also a number of other scientific

Table 1. HEXIT-SAT Optics System

Number of modules	4
Number of nested mirror shells	50
Reflecting coating	200 bi-layers W/Si
Geometrical profile	Wolter I
Focal Length	8000 mm
Total Shell Height	800 mm
Plate Scale	26 arcsec/mm
Material for the mirror walls	Electroformed Ni
Min-Max Top Diameter	112 - 330 mm
Min-Max angles of incidence	0.096 – 0.350 deg
Min-Max wall thickness	0.12 -035 mm
Total Mirror weight (1 module)	95 kg
Field of view (FWHM)	14 arcmin
Single Module Effective Area	75 cm^2 at 40keV
Expected Angular resolution (HEW)	15 arcsec

problems could be studied with an unprecedented flux sensitivity and angular resolution. The core of the mission is represented by the focusing optics system, formed by 4 independent mirror modules, each made of several multilayer coated confocal shells. The focal length is 8 m, obtained by means of an extendable optical bench (that permits to maintain the satellite in the small mission class). A layout of the HEXIT-SAT satellite is shown in Fig. 1, while the main parameters of the optics system are reported in Tab. 1. The sequence design for the thickness of bi-layers along the multilayer stacks will continuously change following a power-law (Joensen et al. 1995). The total on-axis effective area for 4 multilayer modules, not-corrected for the detector efficiencies, is reported in Fig. 2. It should be noted that the cut-off of the effective area around 70 keV is determined by the K absorption edge of Tungsten layers. The fabrication technique for the hard X-ray mirrors is based on the direct replication by Ni electroforming of the multilayer film previously deposited onto a mandrel (Citterio et al. 1999). This approach is an upgrade, after appropriate modifications, of the production process (developed in Italy) successfully used for the Au-coated high throughput optics with high imaging characteristics of the BeppoSAX, JET-X, SWIFT and XMM-Newton soft X-ray experiments. The process adopted for growing the multilayer films is the *Ion Assisted E-beam Deposition*, which permits to coat large-size mandrels still maintaining a low interfacial roughness (see Fig. 3). Concerning the focal plane detectors, the goal to be achieved is to have a system able to match well with the high-energy X-ray multilayer optics performance and, at the same time, able to provide the required characteristics of reliability and robustness over the broad (0.5 - 70 keV) energy range. The angular resolution of the X-ray telescope will be $\simeq$ 15 arcsec Half Power Diameter (HPD), which requires, in the focal plane, a spatial resolution no larger than 0.2-0.3 mm, to sample the Point Spread Function at least with two pixels. The detector not only must have good efficiency at energies beyond 10 keV, but also an optimal response in the ”classical” X-ray band (0.5 - 10 keV), where the HEXIT-SAT telescopes present the largest effective area. A hybrid solution has been therefore envisaged. It is based on the use of solid state detectors covering the 10-70 keV band, placed in series after a CCD or a Silicon Drift Chamber (SDC) which, in turn, has to detect photons between 0.5 and 12 keV (see Fig. 4). The hard X-ray detector choice will be a CdZnTe hybrid solid state detector (the possibility of using CdTe crystals is an alternative solution). CdZnTe detectors combine the room temperature operation with a good spectroscopic performance. Due to the relatively high atomic numbers (49) and to the high density (6.1 g/cm^3), the quantum efficiency is also very good (about 0.99 for a 1 mm thick crystal at 55 keV). Thanks to their low capacitance, CdZnTe detectors allow to reach high energy resolution when an accurate coupling to custom front-end electronics is used. CCD detectors are readily available but require temperatures as low as -90C. SDC have very good energy resolution at higher temperature (-20C), but require some development.

4. The SIMBOL-X mission

The SIMBOL-X mission (Ferrando et al. 2004) is a collaboration led by the CEA/Saclay (France) Institute, and involving French, German, and Italian Institutions (at the moment limited to the Brera Astronomical Observatory but, hopefully, extendable to a large number of INAF researchers, with a possible strong support by ASI). SIMBOL-X has been proposed at the beginning of 2004 to CNES, the French Space Agency, with a launch date foreseen during the 2011 year, in the context of a call for ideas for formation flight missions with a high scientific return.

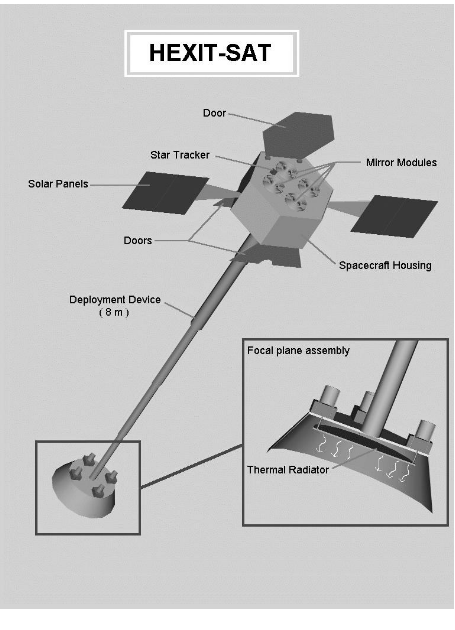

Fig. 1. A layout of the HEXIT-SAT satellite.

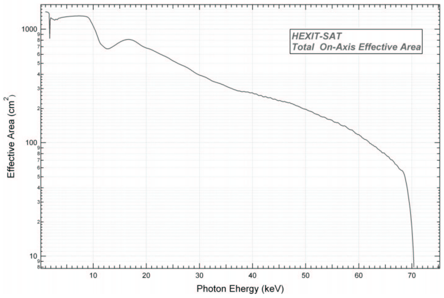

Fig. 2. Total (4 modules) expected effective area for the HEXIT-SAT mirror system.

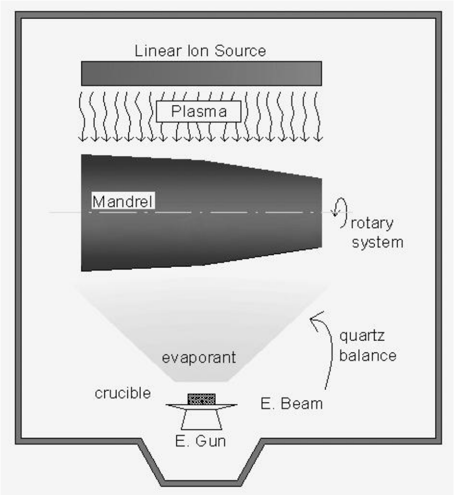

Fig. 3. Scheme of the deposition system that will be adopted to coat the replication mandrels of the HEXIT-SAT mirrors. After being e-beam evaporated, the compactness of the film is increased by the use of a linear ion source.

The SIMBOL-X baseline design relies on a classical Wolter I optics. The gain in maximum energy is achieved by the use of a long focal length (30 m, i.e. 4 times that of XMM-Newton mirrors). Since this cannot fit in a single spacecraft, the mirror and detectors will be flown on two separate satellites in a formation flying configuration (Fig. 5). The necessity to have a stable image quality, as well as to keep the full field of view inside the detector area, dictate the requirements on the formation fly-

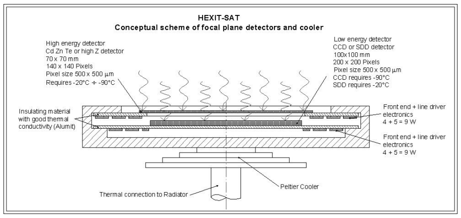

Fig. 4. Scheme of the HEXIT-SAT hybrid detector system, formed by a CdZnTe hard X-ray detector placed in series after a SDC or CCD Si-based soft X-ray detector.

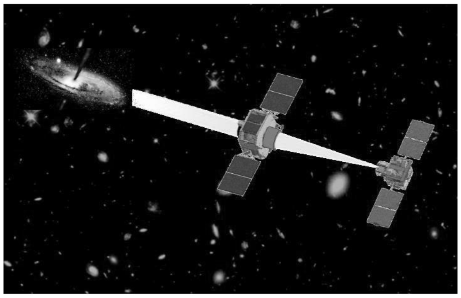

Fig. 5. Layout of the SIMBOL-X mission.

ing stability. For the 30 arcsec HEW, 30 m focal length, nominal mirror, and a detector diameter slightly larger than the FOV these requirements are a position stability of ± 1 cm both along the telescope axis and perpendicular to it. The SIMBOL-X orbit will be circular, at an altitude of 91,000 km, i.e. much higher than the radiation belts, with a low induced instrumental background. In addition, also the perturbations due to the gravity gradient are sufficiently small, a clear advantage for saving the consumables needed to constrain a spacecraft on a forced orbit. The two spacecrafts will be fully equipped with propulsion systems and ranging systems (RF and optical metrology), allowing to meet the formation flying requirements. The mirror spacecraft (master) will be on the circular orbit, while the detector spacecraft (slave) orbit will be forced. SIMBOL-X makes use of conventional single-layer mirrors with very shallow reflection angles. This is an easy way to be pursued from a the point of view of the optical realization, once provided that the problem of small apertures can be solved by the use of focal distances much larger than usual. Thanks to its very long focal length, the aperture diameter is very large, similar to that of an XMM mirror module. However, the reflection angles are much smaller than XMM, allowing us to get a high effective area up to 70 keV. The number of shells assumed is 100, with a height of 60 cm and a minimum diameter of $\simeq$ 30 cm. On the other hand, the SIMBOL-X FOV (6 arcmin FWHM) is $\simeq$ a factor 2 less than HEXIT-SAT (which is based on multiplayer mirrors). The reflecting material will be Platinum, which presents a slightly larger ($\simeq$ 6.5 %) reflection window than Gold. In order to get an optics mass as small as possible (230 kg, in order to be compatible with small mission class) in SIMBOL-X the thickness-to-diameter ratio for mirror walls is diminished of a factor 3.4 with respect to XMM. As a consequence, the angular resolution will tend to be worse, but in any case it is expected to be better than 30 arcsec HEW, in agreement with experimental proofs already obtained. Fig. 6 shows the effective area as a function of energy. 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 1 cm^2 above more than 70 keV (see Fig. 6). Concerning the focal plane assembly, it will follow a hybrid scheme very similar to that already discussed for HEXIT-SAT.

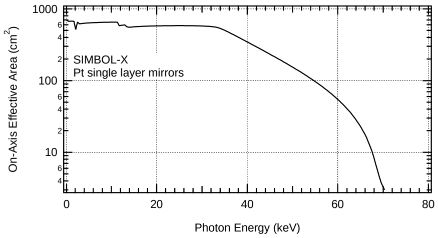

Fig. 6. The SIMBOL-X expected on-axis effective area.

5. Concluding remarks: HEXIT-SAT compared to SIMBOL-X

In Fig. 7 the expected flux sensitivities for HEXIT-SAT and SIMBOL-X are reported. The improvement compared to previous missions based on direct view detectors would be dramatic (for HEXIT-SAT, the gain is ≃ 3 orders of magnitude). At 30 keV photon energy, the flux sensitivity of HEXIT-SAT is about 3 times better than SIMBOL-X and, in addition, it can also rely on a larger operational energy range, while it presents a FOV and HEW a factor 2 better. On the other hand, by using also for SIMBOL-X multilayer-coated mirrors, it would be possible to increase the maximum optics diameter from the current value of 60 cm up to 77 cm. This will determine a large improvement of the effective area and FOV (about a factor 2). The achievable flux sensitivity with the modified SIMBOL-X design, also shown in Fig.7, would then become very similar to that of HEXIT-SAT.

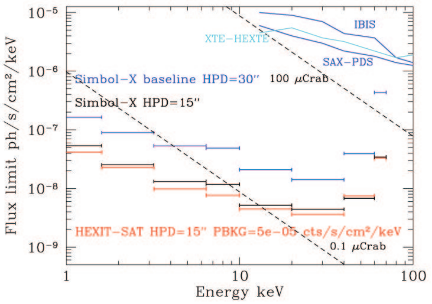

Fig. 7. Flux Sensitivity (S/N = 3) for HEXIT-SAT and SIMBOL-X. The integration time is 1 Msec, while the instrumental backgrounds assumed are 5×10^{-5} cts/s/cm^2/keV and 10^{-4} for HEXIT-SAT and SIMBOL-X respectively. The behaviour for a possible improved version of SIMBOL-X is also plotted (courtesy of F. Fiore, INAF-OAR, Roma).

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