GAME: GRB AND ALL-SKY MONITOR EXPERIMENT

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We describe the GRB and All-sky Monitor Experiment (GAME) mission submitted by a large international collaboration (Italy, Germany, Czech Repubblic, Slovenia, Brazil) in response to the 2012 ESA call for a small mission opportunity for a launch in 2017 and presently under further investigation for subsequent opportunities. The general scientific objective is to perform measurements of key importance for GRB science and to provide the wide astrophysical community of an advanced X-ray all-sky monitoring system. The proposed payload was based on silicon drift detectors (∼1–50 keV), CdZnTe (CZT) detectors (∼15–200 keV) and crystal scintillators in phoswich (NaI/CsI) configuration (∼20 keV–20 MeV), three well established technologies, for a total weight of ∼250 kg and a required power of ∼240 W. Such instrumentation allows a unique, unprecedented and very powerful combination of large field of view (3–4 sr), a broad energy energy band extending from ∼1 keV up to ∼20 MeV, an energy resolution as good as ∼250 eV in the 1–30 keV energy range, a source location accuracy of ∼1 arcmin. The mission profile included a launch (e.g., by Vega) into a low Earth orbit, a baseline sky scanning mode plus pointed observations of regions of particular interest, data transmission to ground via X-band (4.8 Gb/orbit, Alcantara and Malindi ground stations), and prompt transmission of GRB / transient triggers.

Keywords: X-ray astronomy: instrumentation; gamma-ray bursts; X-ray astronomy: all-sky monitoring

1. Scientific Objectives

The proposed GAME mission has two main scientific objectives:

a) measuring the photon spectrum and timing of the prompt emission of gamma ray bursts (GRBs) over a broad energy band, from 1 keV to 20 MeV, combined with arcmin location accuracy;

b) monitoring the X-ray sky in the 1 to 200 keV band with a few arcmin source location accuracy and a few mCrab daily sensitivity over a large field of view (FOV).

1.1. *Gamma-ray bursts*

Discovered in the late 1960s by military satellites and revealed to the scientific community in 1973, GRBs are one of the most intriguing "mysteries" for modern science.[1–3] Indeed, despite the fact that they are very bright (fluences up to more than 10^{-4} erg cm^{-2} released in a few tens of s) and very frequent (about 0.8/day as measured by low Earth orbit satellites) phenomena, their origin and the physics at the basis of their complex emission remained mostly obscure for more than 20 years. This remains true even today, despite the huge observational efforts of the past decades, which have provided, among other things, 1) a good characterization of the bursts temporal and spectral properties, 2) the accurate localization and discovery of their multi-wavelength afterglow emission by BeppoSAX, 3) the determination of their cosmological distance scale and the evidence of a connection with peculiar type Ib/c SNe, our understanding of the GRB phenomenon is still affected by several relevant open issues, both from the observational and theoretical points of view. Many of these questions can be addressed only by broad band sensitive measurements of the prompt emission, from several MeVs down to ∼1 keV. In particular, the extension of the energy band down to soft X-rays is of key importance for testing prompt emission models, for studying the properties of the circum-burst environment from the detection of transient absorption features and/or variable NH, for the investigation of X-ray Flashes (XRFs, which may constitute the bulk of the true GRB population), and for increasing the detection rate of high redshift GRBs (of paramount importance for the study of the early Universe). It is also fundamental, for the advancement of GRB science, to have a devoted mission in the

>2020 time-frame in order to continue the alert, presently provided by the Swift satellite, of space and ground multi-wavelength telescopes.

GAME will give the answer to still other open questions of fundamental importance for the physics of the GRB phenomenon and for exploiting GRBs as cosmological rulers, among which are:

- to detect expected transient X-ray absorption column and absorption features for tens of medium/bright GRBs per year. These measurements are of paramount importance for the understanding of the properties of the Circum-Burst Matter (CBM) and hence the nature of GRB progenitors (a still fundamental open issue in the field). In addition, the detection of transient features[4] can allow the determination of the GRB redshift to be compared, when it is the case, with that determined from the optical/NIR lines.
- to perform unbiased measurements of time resolved spectra within single GRBs down to about 1 keV. This is crucial for testing models[5,6] of GRB prompt emission (still to be settled despite the considerable amount of observations).
- to provide a substantial increase with respect to the past and current missions) in the detection rate of X-Ray Flashes (XRF), a sub-class of soft / ultra-soft events which could constitute the bulk of the GRB population and could be the missing link between high luminosity hard bursts and the low luminosity/relatively soft GRBs with associated SN events.[7,8]
- to significantly increase the GRB detection up to very high redshift ($z > 8$), which is of fundamental importance for the study of evolutionary effects, the tracing of the star formation rate, ISM evolution, and possibly unveiling population III stars.[9]
- to perform an accurate determination of spectral peak energy, which is a fundamental quantity for the test and study of spectrum-energy correlations and the possible use of GRBs as cosmological probes.[10–12]
- to provide fast (within 1 min) and accurate (within 1–2 arcmin) location of the detected GRBs to allow their prompt multi-wavelength follow-up with ground and space telescopes, thus leading to the identification of the optical counterparts and/or host galaxies and to the estimate of the redshift, a fundamental measurement for the scientific goals listed above.

We remark that GRB science is of interest to several fields of modern astrophysics and cosmology, such as: physics of matter under extreme conditions, core-collapse and black-hole formation in massive stars, peculiar SNe, star formation rate evolution up to the early Universe, first generation of stars, measurement of the geometry and expansion rate of the Universe. These topics fit very well the ESA Cosmic Vision 2015–2025 plan, in particular, themes 3.3 ("Matter under extreme conditions"), 4.3 ("The evolving violent Universe") and 4.1 ("The early Universe") and of the recommendations of the ASTRONET Science Vision and Road-map (in particular, Theme 2: “Do we understand the extremes of the Universe?”)

1.2. *X-ray all-sky monitoring*

Besides GRB science, an instrumentation with a large FOV (order of a few sr), an energy band extending down to 1 keV, and a source location capability in the arcmin range, can also be devoted to X-ray all-sky monitoring observations. As stressed also in the ASTRONET Science Vision and Road map, the wide-field X-ray monitoring is a crucial task for X-ray Astronomy, due to the large variability of almost all classes of sources. However, the most sensitive observatories have in general a narrow FOV ($\sim 1^\circ$ or less) and are designed to perform studies of individual sources. Instead the perspectives of wide field monitoring are not satisfactory: RXTE/ASM completed its mission operations and ISS/MAXI will likely operate for the next 2–4 years. In addition to the sky survey, we plan to also perform follow-up broadband (1–200 keV) observations of transient sources in outbursts previously discovered with the scanning mode. Also, deep observations of persistent but variable sources are foreseen for studying their time behavior and their spectral evolution. We also expect to trigger many TOO multi-wavelength observations (from radio to optical to X-rays). Most of the sources that will be detected and studied through X-ray all-sky monitoring provide unique insights on the properties of neutron stars and black-holes and the physics of matter accretion onto these objects. Thus, this science, in addition to the ASTRONET recommendations, fits very well the Cosmic Vision 2015–2025 plan themes “Matter under extreme conditions” (3.3) and “The evolving violent Universe” (4.3).

Concerning the all-sky monitoring, the scientific objectives of GAME include:

- detection and localization within a few arcmin of Soft Gamma-ray Repeaters (SGR), X-ray bursts (XRB) and many other classes of galactic X-Ray Transients (XRT), like, e.g., Galactic low and high mass X-ray binaries in outburst, cataclysmic variables, accreting ms pulsars, etc., for spectral and timing studies;
- to trigger follow-up observations by ground and space observatories, a fundamental service for the world-wide community;
- to perform an all-sky survey in the hard X-ray band up to 200 keV, contemporary to that of eROSITA at lower energies.

The above science goals address fundamental questions of the ESA Cosmic Vision 2015–2025, like the following: what are the fundamental laws of the Universe? What is the physics of matter under extreme conditions? How did the Universe originate and what is made of? GRBs not only allow us to investigate the physics of the most energetic phenomena, but are expected to be become, with the mission we are proposing, a new well established probe of cosmology theories.

2. Scientific Requirements

The scientific goals we have discussed in the previous section define the instrumentation and mission profile requirements.

2.1. *Payload requirements*

The scientific requirements for the instrumentation can be summarized as follows.

- Energy pass-band: for GRBs, from ∼1 keV up to ∼20 MeV. The lower threshold is fundamental for the study of transient X-ray absorption features and the substantial increase in the detection and study of XRFs and high-z GRBs. The broad band is of key importance for the identification estimate of fundamental spectral parameters. For all sky X-ray monitoring, from ∼1 keV up to ∼200 keV. The extension to the hard X-rays with good efficiency optimizes the spectral sensitivity to the hardest X-ray transients and SGRs.
- Energy resolution: 300 eV for photon energies $<$10 keV. It is required for the study of the expected absorption features from GRBs. An energy resolution $<$15% for photon energies $>$50 keV is enough for accurate measurement of the peak energy of the νFν spectrum.
- Source location accuracy: a few arcmin. This is required to trigger and allow follow-up observations of the detected transients by other telescopes, but it is also essential for fulfilling the GRB scientific objectives, the all-sky monitor functionality and the X-ray all-sky survey science objectives.
- Field of View (FOV): about 4 sr (Partially Coded Field of View, PCFOV) combined with a sensitivity of ∼500 mCrab (in 1s integration time) in the 3-50 keV energy band. This is required in order to allow detection and localization of ∼150 GRBs and XRFs per year (including ∼2–4 events at z $>$ 6), to perform a sensitive time resolved spectroscopy of ∼2/3 of them and to use the instrument as an all-sky monitor for Galactic transients (SGRs and other XRTs).
- Average effective area: ∼1000 cm^2 up to 200 keV, ∼500 cm^2 up to ∼20 MeV within a FOV of 2 sr. This is required to allow sensitive broad band spectroscopy of GRBs (for GRB physics and cosmology studies) and to increase the overall trigger efficiency, especially for short (and spectrally hard) GRBs.
- On board data handling electronics. This is required to identify GRB trigger, discrimination of false triggers and fast source position reconstruction in order to allow prompt alert distribution and follow-up observations.

2.2. *Mission profile requirements*

The scientific objectives of GAME require a low and stable background level, thus a flight in a nearly equatorial low Earth orbit (∼600 km) with a desirable inclination

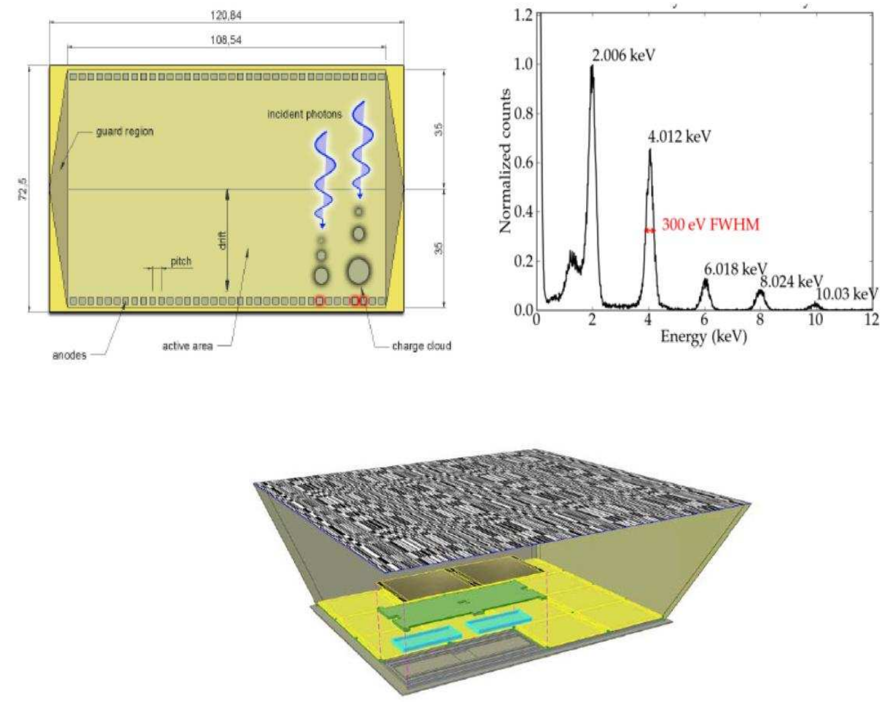

Fig. 1. X-Ray Monitor (XRM): sketch of the detector's working principle (top left), spectroscopic performance (top right) and sketch of a single camera assembly.

lower than 5°. This also allows the reduction of radiation damage to the detectors and ASICs. Also, the achievement of the scientific objectives and providing prompt triggers requires the capability of promptly transmitting to the ground alerts with coordinates and basic information of at least the detected GRBs. Compatibly with solar and thus thermal constraints, the orientation of the spacecraft is required to be continuously drifting to cover in each orbit a large fraction of the sky. For particularly interesting sky fields pointed observations will be also required.

3. The Proposed GAME Payload

The approach is to optimize instrumentation for both GRB prompt emission study and the all-sky X-ray monitoring. For the GRB study, we propose a broad band (1–20000 keV) GRB monitor with an imaging capability at low energies, while for the ASM we propose an imaging capability in the entire band (1–50 keV) in which we want to work, with an extension up to 200 keV in a narrower FOV. The instrumentation proposed consists of an X-Ray Monitor, XRM (Fig. 1), made of a set of 9 pairs of Si based independent imaging cameras (1–50 keV). Each pair

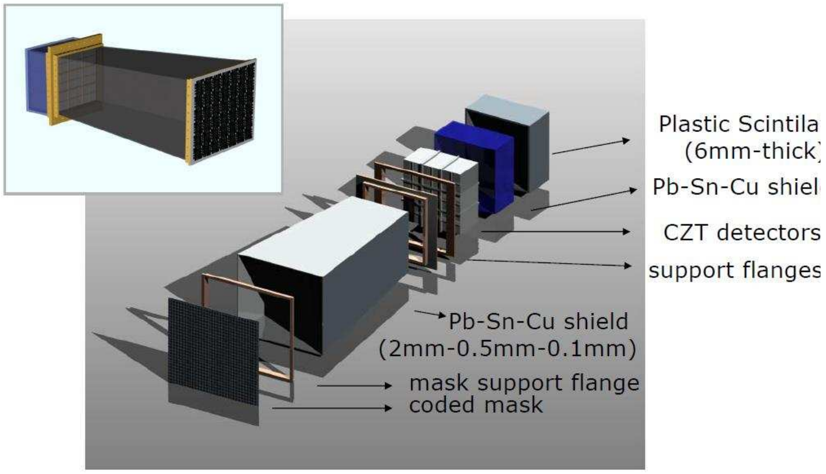

Fig. 2. Sketch of the Hard X-ray Imager (HXI).

of cameras consists of a wide field Silicon Drift detectors (initially developed for the ALICE experiment for the CERN/LHC accelerator and later adapted for space astronomy, e.g., for the LOFT mission[13]), surmounted by orthogonally located 1D coded masks, to get, for each pair, a bi-dimensional (2D) imaging. Instead the extension of the monitoring at hard X-ray energies is obtained with a CZT position sensitive detector surmounted by a 2D coded mask working in the 10–200 keV energy range[14] (Hard X-ray Imager, HXI, Fig. 2). The high energy portion of the GRB spectrum (20–20000 keV) is measured with 2 modules of 4 NaI(Tl)/CsI(Na) scintillator units in phoswich configuration[15] (Soft Gamma-ray Spectrometer, SGS; Fig. 3). A possible overall payload configuration is illustrated in Fig. 4.

3.1. *Instrument conceptual design and key characteristics*

XRM is a set of Si-detectors and coded-mask X-ray cameras, 3 pairs for each sky direction. In each camera the detection plane is made of 2x2 Silicon Drift Detector (SDD) tiles. In a tile (active area ∼7x7 cm^{-2}, 450μ thickness) a cloud of electrons generated by interaction of the X-ray photon with Si is drifted toward the read out anodes driven by a constant electric field.[16] The Si tile is electrically divided in two halves with 2 series of about 350 anodes (pitch ∼200μ) at the two edges and the highest voltage along the symmetry axis. The requirement of fine pitch, small parasitic capacitance and low power consumption require a high density read-out system based on ASIC (Application Specific Integrated Circuit) that includes several independent, low noise complete spectroscopic chain made of charge preamplifier, pulse shaper and amplifier, discriminator, etc. The detection plane of each camera

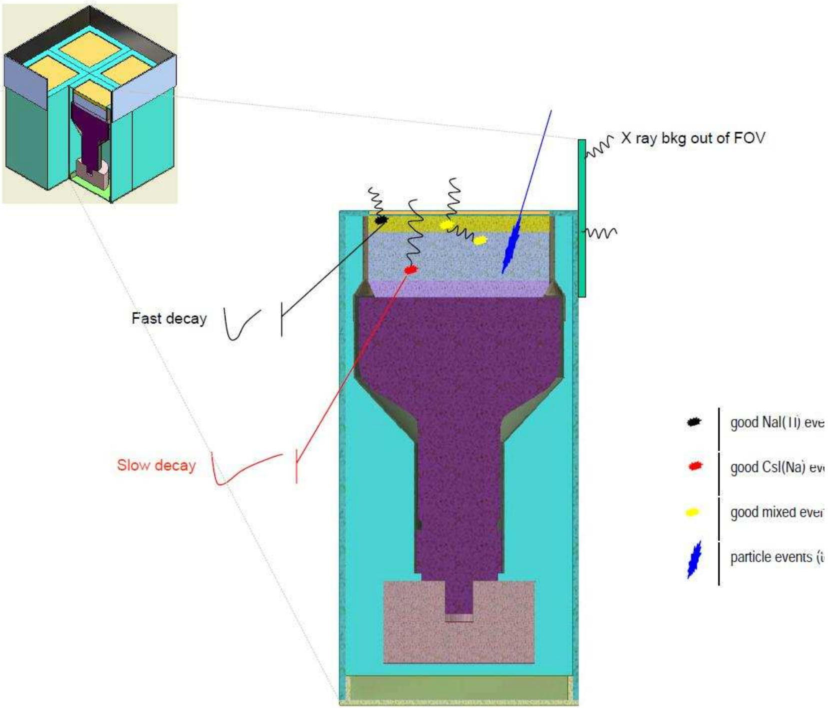

Fig. 3. Soft Gamma-ray Spectrometer (SGS): sketch of a single phoswich unit assembly and working principle and, in top left position, sketch of 4 units assembly.

is surmounted by 1D coded mask placed at 20 cm distance.

The SGS is composed by 8 scintillator units, each one being an independent detector in which the active part is made by 1 thick cm thick NaI(Tl) (top) and 4 cm CsI(Na) (bottom) scintillators both viewed by a single Photomultiplier Tube (PMT) (phoswich configuration). The useful cross section is 14x14 cm^{-2}. The PMT signal is analyzed in both shape and amplitude in order to measure the energy losses separately in NaI(Tl) and CsI(Na). In the low energy band (20–200 keV) of SGS operation, the CsI(Na) will have the role of actively shielding and thus rejecting the background (BKG) coming from the bottom (e.g., terrestrial albedo), while in the 100-20000 keV, the CsI(Na) will act as main detectors. In this energy band also the losses in both crystal materials will be analyzed. Each set of 4 phoswich units will be passively collimated to further reduce the diffuse background. Each set of 4 phoswich units will be offset by 10° with respect to the HXI axis to cover most of the FOV of the XRM. A gain control system based on the SAX/PDS design will be implemented. A ground calibration campaign will be performed for each instrument before flight, using the already available X-ray facilities in the GAME consortium (e.g., the LARIX facility at the University of Ferrara, already used for the INTEGRAL/JEM-X ground calibration). The main scientific characteristics of the GAME instruments, together with a summary of the required resources, are

Table 1. Main characteristics and resources of the GAME instruments.

	XRM	HXI	SGS
Energy range [keV]	1–50	10–200	20–20,000
Energy resolution FWHM	250 [eV]	5 keV@60 keV	15%@60 keV
Time resolution [μs]	$\sim$10	$\sim$10	$\sim$1
Effective area [cm^2]	>550 in FCFoV (through mask)	$\sim$170	$\sim$1500@300 keV
Angular resolution	5 arcmin	$\sim$1.5°	–
Point source location accuracy	<1 arcmin	$\sim$30 arcmin	–
Field of view	$\sim$3.0 sr FCFoV $\sim$5.4 sr PCFoV	20° × 20° FWHM	$\sim$2.5 sr (FWHM)
Sensitivity (5-σ)	300 mCrab or $\sim$2.5 ph/cm^2/s in 1 s, FCFOV $\sim$2 mCrab (50 ks) (FCFOV)	$\sim$10 mCrab (1 day)	$\sim$1 Crab in 1 s
Mass plus 20% contigency [kg]	140	30	80
Volume [mm^3]	1307 × 1316 × 700 (whole)	375 × 375 × 550	283 × 283 × 320 (1 unit)
Power plus 20% contigency [w]	100	20	30
Data rate (orbit average) kbit/s	$\sim$750	3.2	$\sim$40

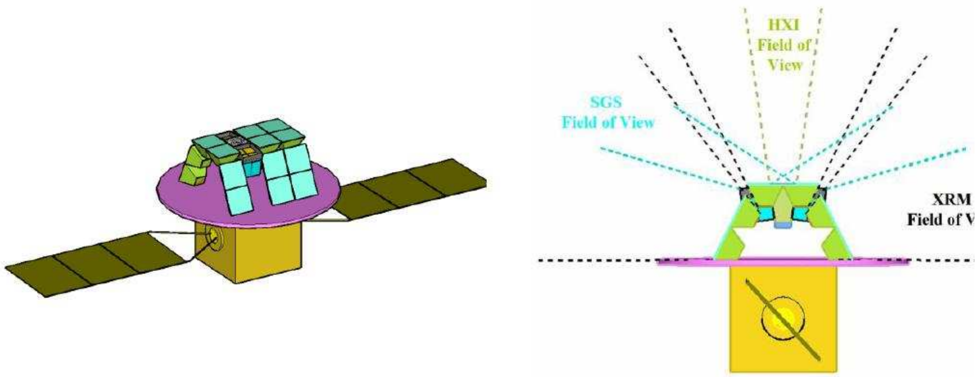

Fig. 4. An hypothesis of allocation of XRM, HXI and SGS. The dimensions of the bus are $\sim$1 m^3.

reported in Table 1.

4. Mission Profile

Both the orbit and the payload volume and mass budget are compatible with the Vega launcher. Although the satellite is not compatible with the Vega piggy-back approach, its compactness and reduced size and weight, may make possible a dual launch approach if also the second satellite manifest interest as Vega piggy-back.

Table 2. Main characteristics of the whole satellite.

Parameter	Value
Mass	∼500 kg (PMM total), ∼250 kg (GAME payload)
Power	∼240 W (total), ∼150 W (GAME payload)
Telemetry budget	∼4.8 Gb/orbit
Telemetry downlink	X-band, ∼4.0 Mbps for 15 passes/day/station (10 min transmission/pass)
Ground stations	Alcantara, Malindi

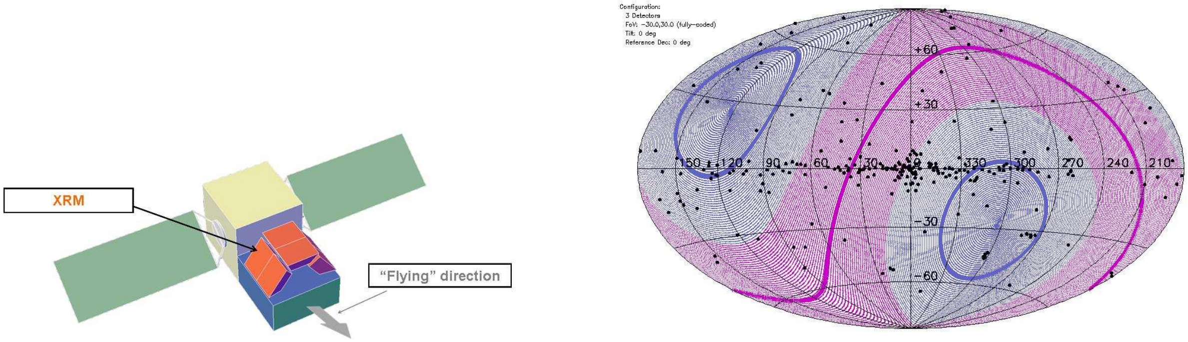

Fig. 5. Left: flying configuration and pointing strategy of the satellite (for clarity, only 6 units of the XRM are shown). Right: XRM sky coverage (every orbit).

The scientific objectives of GAME require a low and stable background level, thus a flight in a nearly equatorial low Earth (∼600 km, < 5°) orbit. The observation strategy has been defined combining: 1) scientific goals; 2) operational constraints imposed by the payload (e.g., Sun illumination of the instrument FOV is not allowed); 3) simplest mission management; 4) efficient use of platform capability. Consequently two operative modes have been envisaged: scanning mode and pointing mode. The scanning mode is the default observational mode. It consists of continuously orienting the spacecraft, in such a way that the negative direction of the platform axis on which the instruments are located (Fig. 5), compatibly with the Sun constraints, will continuously point at the Earth center. In this way a large part of the sky will be observed in one orbit with XRM and SGS. When the Sun prevents us from performing the scanning strategy, the orientation of the satellite

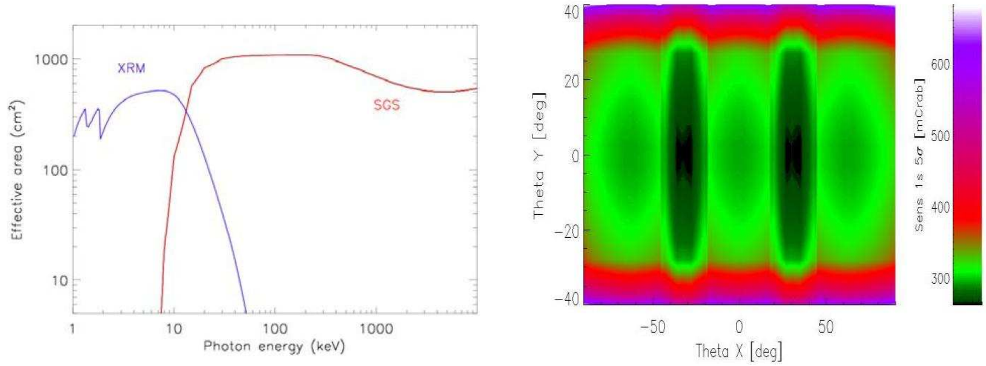

Fig. 6. Effective area (left) and sensitivity (5σ, 1s; right) within the FOV of the XRM.

will drift to directions that prevent a Sun illumination of the instrument FOV keeping constantly a null Sun aspect angle. During these time periods, in addition to the sky observations, the Earth will be observed with the possibility of detecting and localizing Terrestrial Gamma-ray Flashes (TGFs). These are very spiky events whose emission physics is still the subject of discussion and are possible probes of terrestrial thunderstorms.[17] Pointed observations of particularly interesting regions previously scanned or sky regions requested for TOO observations will be also performed. In this case the sky accessible field is reduced during orbit daylight period by zero Sun aspect angle. The expected mission lifetime is 4 years, extendible to further 3 years. The foreseen telemetry budget with no data compression is compatible with the use of an X-band transmitter. For the prompt transmission to ground of coordinates and basic information of detected GRBs or X-ray transients, a real time link with Earth is foreseen. A possibility we are evaluating is an innovative telemetry system, STRADIUM, realized by an Italian team in collaboration with the Italian Space Agency. It provides a near real time, bi-directional, continuous telemetry/telecommands link. It exploits the IRIDIUM network.[18]

The main parameters of the entire satellite are reported in Table 2. The Brazilian PMM platform allows an absolute pointing accuracy of 3 arcmin (3σ) and an attitude determination of 0.3 arcmin (3σ). The XRM and the HXI require their pointing direction to be known better than 1 arcmin in order to correctly reconstruct their images. A pre-launch optical alignment with the star trackers will ensure this. The baseline is a Vega launch devoted to GAME. An alternative launch option may include the use of Vega in full piggy-back configuration, which is compatible with the mass and volumes of the proposed bus and payload.

5. Expected Performances

Figures 6 to 8 show examples of the expected scientific performances of GAME. In Fig. 6 we show the effective area as a function of energy and the 5σ sensitivity in 1s observation time of the XRM in its FOV. As can be seen, we have at least

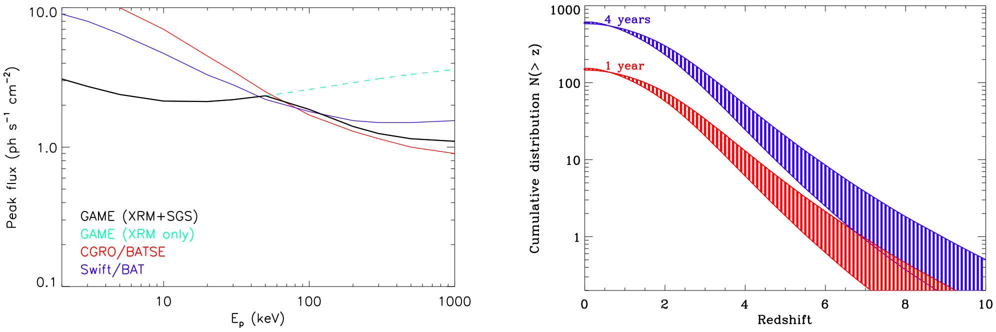

Fig. 7. Left panel (adapted from a figure by Ref. 21): expected GAME flux sensitivity as a function of GRB spectral peak energy (Ep) compared with that of BATSE and Swift/BAT. Right panel: cumulative redshift distribution of long GRBs predicted for GAME. Shaded regions take into account the error on the evolution parameters: the red (blue) shaded region refers to 1yr (4yr) of mission.

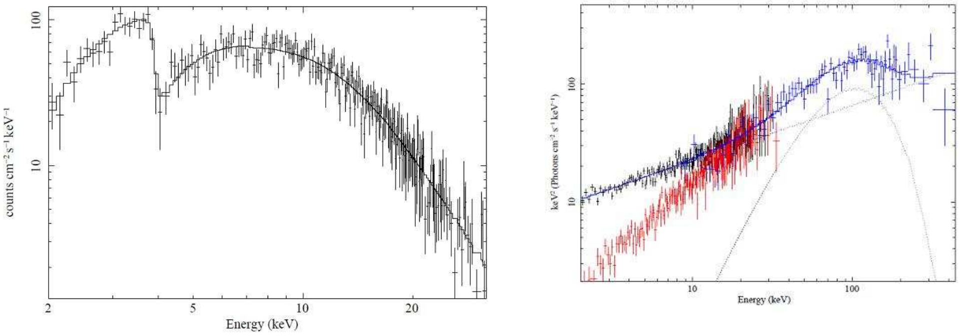

Fig. 8. Left: the X-ray transient absorption feature observed with BeppoSAX/WFC in the first 13 s of GRB 990705[4] would be detected by GAME with a significance larger than 10σ. Right: simulated XRM spectra of the first ∼50s of GRB 090618 obtained by assuming either the Band function (black) or the power-law plus black-body model (red) which equally fit[20] the Fermi/GBM measured spectrum, which is also shown (blue). The black-body plus power-law model components best-fitting the Fermi/GBM spectrum are also shown (black dashed lines).

500 cm^{-2} in most of its FOV. In Fig. 7 left, we show the expected GAME flux sensitivity as a function of GRB spectral peak energy (Ep) compared with that of BATSE and Swift/BAT, while in Fig. 7 right we show the cumulative redshift distribution of long GRBs predicted for GAME. This distribution has been obtained assuming a broken power-law GRB luminosity function and a pure density evolution (see Ref. 19 for the details of the model). The model's free parameters has been

determined by fitting the observed differential number counts and the observed redshift distribution of a redshift complete sample of bright Swift GRBs.[19] Without any change in the model's free parameters, the same model is able to reproduce the redshift distribution of GRBs at the Swift sensitivity as collected by GROND. Shaded regions take into account the error on the evolution parameters: the red (blue) shaded region refers to 1yr (4yr) of mission. At the flux limit of GAME we predict up to 16 GRBs to lie at z>6 in the full 4 yr mission life. For a comparison, in 7 years of operations, only 4 GRBs detected by Swift have a measured redshift higher than 6. In Fig. 8 (left) we compare the X-ray transient absorption feature at 3.8 keV observed with BeppoSAX/WFC in the first 13s of GRB 990705[4] and that expected if that feature would be observed with GAME. The 3.8 keV edge would be detected with a significance of more than 12σ against the $\sim 4\sigma$ significance obtained with SAX/WFC. In Fig. 8 (right) we show the simulated WFM spectra of the first ∼50s of GRB 090618 obtained by assuming either the Band function or the power-law plus black-body model (red) which equally fit the Fermi/GBM measured spectrum,[20] which is also shown. As can be seen, only thanks to the extension of the spectral measurement below 10 keV allowed by the XRM, it is possible to discriminate between the Band and black-body plus power-law models.

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