PROCEEDINGS OF SCIENCE

The Cosmic X-ray Background explorer (*CXBe*)

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Synthesis models of the diffuse Cosmic X-ray Background (CXB) suggest that it can be resolved into discrete sources, primarily Active Galactic Nuclei (AGNs). Measuring the CXB accurately offers a unique probe to study the AGN population in the nearby Universe. Current hard X-ray instruments suffer from the time-dependent background and cross-calibration issues. As a result, their measurements of the CXB normalization have an uncertainty of the order of ~15%. We present the concept and simulated performances of a CXB detector, which could be operated on different platforms. With a 16-U CubeSat mission running for more than two years in space, such a detector could measure the CXB normalization with ~1% uncertainty.

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1. Introduction

The diffuse Cosmic X-ray Background (CXB), peaking at 30 keV, is primarily produced by the superposition of the emission from Supermassive Black-Holes (SMBH) in Active Galactic Nuclei (AGN) accreting close to the Eddington limit. The CXB, therefore, serves as a constraint on the integrated SMBH growth in the Universe and on the accretion physics and obscuration in AGN [1]. The discovery of the CXB [2] by Riccardo Giacconi was awarded the Nobel Prize for Physics in 2002. The CXB spectrum has been subsequently measured by many experiments (shown in Fig.1), as of systematics like inaccurate in-orbit calibration and residual background, the CXB flux and spectrum measured by many experiments disagree with each other by up to 10%-15% [17]. Resolving the CXB was among the primary science goals of missions like XMM-Newton [3] and Chandra [4, 5]. As a result, the CXB is nearly (>93%) resolved into point-like AGN at soft X-rays (below 10 keV) [6, 7], whereas the resolved percentage is decreasing with increasing energy (<39% at <20 keV and 2% at 50 keV) [8].

In recent years, great progress has been made in understanding the high-energy emission from AGN with subsequent insights into the process of SMBH accretion, the impact of SMBH on galaxy evolution, and the ultimate composition of the CXB. However, the challenges of observations at hard (> 10 keV) X-ray energies mean that direct knowledge of the AGNs that produce the bulk of the CXB has remained elusive. INTEGRAL, Swift/BAT and NuSTAR have advanced our understanding of the connections between obscuration, accretion physics, and the high-energy X-ray emission from AGNs, indicating a wide range of covering factors among obscured AGN. Previously X-ray-detected AGNs are also significantly more obscured than can be determined through soft X-rays alone; possibly indicating a large Compton-thick fraction of ~30% [9]. Furthermore, some luminous obscured AGN with no previous X-ray detections are extremely weak implying absorption column densities in excess of $10^{25}\mathrm{cm}^{-2}$ [10, 11]. While such sources are known locally (e.g., the canonical Seyfert 2 NGC 1068), their general abundance is poorly understood, in part because their X-ray emission, along with many other AGN signatures, is heavily suppressed. The existence of extremely obscured sources can strongly impact estimates of the total AGN power and the global radiative efficiency (e.g. [12]). The physical nature of the obscuration arises from a parsec-scale "torus" or from a range of scales from broad-line region clouds to galaxy-scale gas (e.g., [1, 13]). Soft X-ray observations often degenerate between obscuration by small-scale clumpy material and smooth, large-scale clouds, but hard X-ray observations can constrain the reflection component and provide important additional constraints on the geometry [14, 15].

Extrapolating stacked AGN spectra accounting for the CXB spectrum below 10 keV does not reproduce the CXB at hard X-rays. A large population of Compton thick sources (where the density of obscuring material is high enough for Compton scattering to dominate) has been hypothesized to fill the gap. The comparison of the observed CXB with the results of synthesis models puts constraints on the fraction of AGNs with different degrees of obscuration and reflection. The relation between reflection and absorption contains important information on the average AGN inner geometry. The contribution of Compton thick (CTK) sources to the CXB flux at 30 keV is estimated to be 4%-6% based on the CXB synthesis [1]. As this is twice less than the 10%-15% uncertainty this contribution is highly dependent on the CXB spectral uncertainties. The Cosmic X-ray Background explorer (CXBe) will result in an accurate measurement of the CXB with ~1%

uncertainty after two years of observation, a very significant improvement [16].

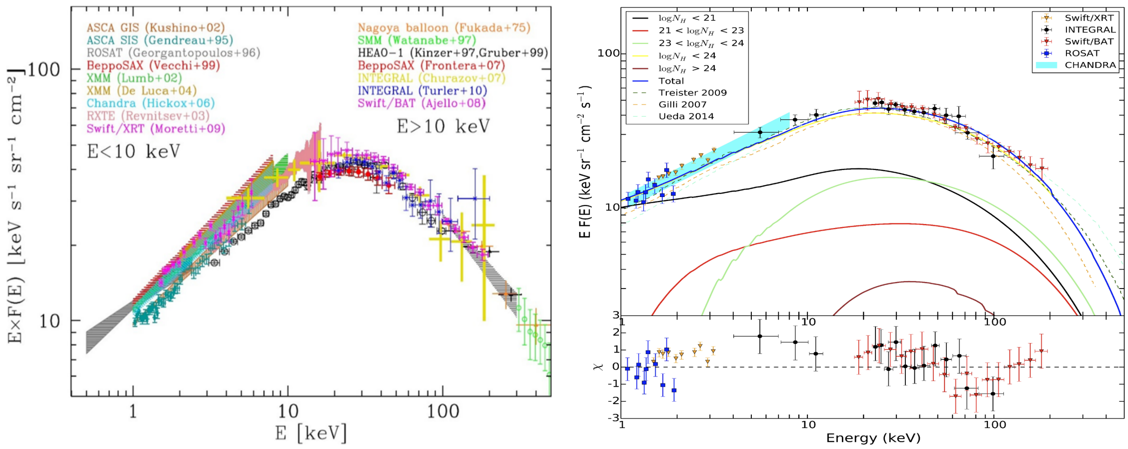

Figure 1: Left: current measurements of the CXB by multi missions [17, and reference there in], where discrepancies are up to 10%-15%. Right: the contribution of Compton thick (CTK) sources to the CXB flux at 30 keV is estimated to be 4%-6% based on the CXB synthesis [18].

2. Instrument concept

Our project aims at developing the Cosmic X-ray Background explorer (CXBe), primarily targeting a measurement of the CXB with an uncertainty of 1%. In order to achieve that, instrumental background, energy and detection efficiency need to be meticulously and constantly measured during observations. The detector we proposed here utilizes passive collimators and onboard obturators to model the fluxes registered in the detector. Collimators are used to block surrounding emissions with energy-dependent transparency to reduce the contamination out of the FoV. Obturators will periodically shield the aperture of the collimator, and introduce a modulation of in-FoV components to separate them from the instrument's background noise. To drive such obturators, a compact wheel system is designed. Overall, the detector consists of an array of collimated spectrometers with rotating obturators on top of the collimators. We propose to use a new generation of $CeBr_3$ scintillating crystals, which have been studied to assess their suitability as spectrometer modules for space missions. We will adapt the POLAR-2 [19] electronic for the 64 channels SiPM array readout. A Front-End Electronics (FEE) board (CITIROC-1A ASICs) is equipped for each polarimeter module of POLAR to power (temperature regulated) and readout the SiPM channels, define the trigger logic, and communicate with a Back-End Electronics (BEE) board connected behind. The BEE board takes care of power supply, overall data acquisition, communication with the platform and mission control, etc.

We have integrated our detector into a 12-Unit (U) CubeSat payload, translating to 2*2*3 U (one U corresponds to 10*10*10 cm^3). Such a configuration is shown in the left panel of Fig. 2, where the transparent pink box symbolizes 12 U as a reference. It allows the placement of 18 tubes (each includes a collimator and a spectrometer), all of which have the same dimensions: 28 cm in height and 35 mm in external diameter. The tubes are placed along a dual-ring structure. The 6 inner tubes will be shaded by the 12 outer ones and get less background from the sides, allowing to study the systematics of the background. The compact electronics adapted from POLAR-2 will be placed beneath the wheel system in the centre to power and communicate with the motor and spectrometers, the total power consumption is ~30 W. The necessary platform modules (e.g., power, communication and orbit control) could occupy the corners and sides or another 4-U. This very conservative configuration with 18 tubes is chosen to bring a lot of redundancy to fight systematic effects. A smaller number of tubes (as low as 4 tubes as seen in the right panel of Fig. 4) is possible if considering only statistical effects. Smaller CubeSat (4U, 8U) could probably reach the scientific goals if sacrificing redundancy but could require longer exposure to understand systematical effects due to the space environment.

Another configuration for a Station-based platform is shown in the right panel of Fig. 2. It is based on four groups, each containing four tubes that are twice the size of the CubeSat version. The 3*3 groups have a dimension of 520*520*500 mm^3). This provides a collecting area four times bigger than the CubeSat version. Four groups of obturators are placed on the top, each including a symmetrical rotating sector (opening angle is 90°). Neighbouring obturators are counter-rotating to compensate for angular momentum. The wheel system is simplified as it needs unidirectional rotation.

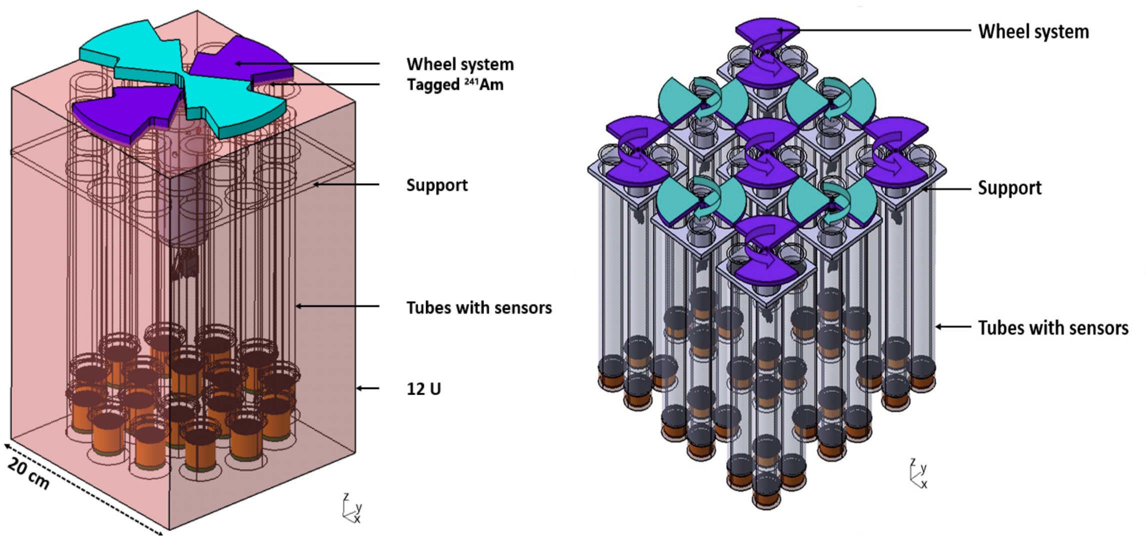

Figure 2: Left: a CubeSat configuration (12U, 200*200*300 mm^3), where 18 detector tubes are placed. Right: a payload configuration (520*520*500 mm^3). Each of the 3*3 detector groups has 4 detector units and one rotating obturator system.

CXBe will employ tagged radioactive sources for absolute calibration on the ground and in orbit. The alpha decay of ^{241}Am produces ~5 MeV alpha particles and X-ray photons (peaking at 13.9 keV, 17.8 keV, 26.4 keV, and mainly 59.6 keV), which can be embedded in a plastic scintillator to mark the decay time. Extremely low activity sources (200 Bq) are enough for this purpose and two tagged ^{241}Am sources will be attached beneath the bottom obturator for calibrations. Selecting coincident events in the spectrometers allows us to continuously characterize the detection efficiency and the Energy-Channel (EC) correlation of the detectors (details please refer to [16]).

3. Simulated performance

We use the CubeSat configuration to evaluate the performance (the station-based version would be better). The spectral responses and the background are generated using the Geant4 simulation package [20]. For known sources we used the Swift-BAT catalogue [21]; the CXB template is from [22]. The derived count rate (10-100 keV) distribution (by convolving spectral templates with detector responses) over the sky is shown in the left panel of Fig.3 with a bin size corresponding to the FoV of a tube. On average one source is contributing per sky bin. The space environmental background is the main concern in a Low-Earth Orbit (LEO). The spectra of the different components are considered to be isotropic inputs to the instrument simulator. The anticipated background rates are shown in the right panel of Fig.3.

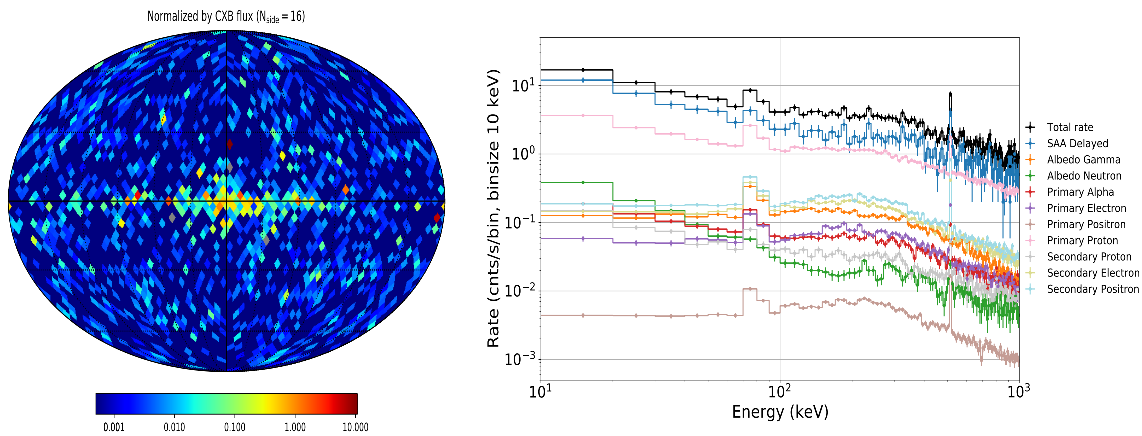

Figure 3: Left: distribution of the relative count rate of the Swift-BAT source catalogue [21] in our instrument (normalized by the CXB rate, i.e., 0.129 counts/s/tube). Right: Simulated spectra of different background components. The total rate of 72.56 cnts/s in 10-100 keV is used in this paper for the estimation of measurement accuracy of the CXB.

We filter out regions that include $|b| < 10^\circ$, the Magellanic clouds, and (non-AGN) sources. Most remaining sources at high galactic latitude are nearby CVs, stars and unidentified sources, which are the bright components of the GRXE population. As shown in the left panel of Fig.4, globally about 23% of the sky will be disregarded.

The statistical accuracy of the CXB measurement can be estimated as $P_{\rm sta} = (\sqrt{C+B+U})/C$, where C, B and U represent the total number of counts detected from the CXB, the instrumental background, known galactic X-ray sources and of the unresolved GRXE in all open tubes from all the remaining sky regions. Fig4 right panel gives the resulting statistical accuracy of the CXB normalization as a function of the number of detector modules and mission time. With 18 detector tubes operating for more than two years, the statistical accuracy will be $< 0.25\%$. The very large redundancy provided by 18 tubes and the data set representing orders of magnitude more events than what the statistical error requires will allow to study and correct all the possible systematics due to the space environment. Therefore the final uncertainty over 2 years of mission will be limited by the ground calibration performance which we estimate at $\sim 1\%$.

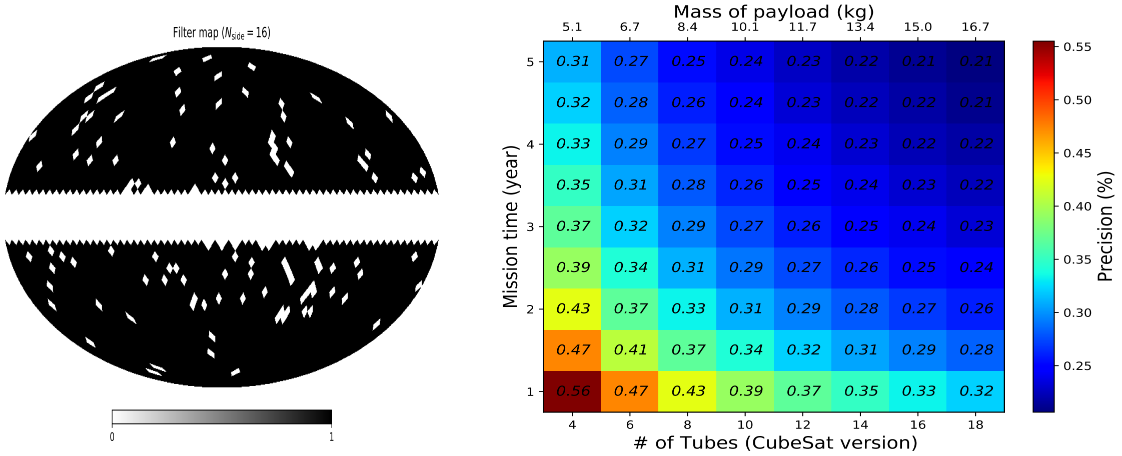

Figure 4: Left: Filter map in galactic coordinates, the white pixels will be disregarded in the analysis (globally about 23% of the whole sky). Right: Expected statistical precision of CXB measurement versus mission time and the number of detector tubes.

4. Summary and discussion

The CXB is made of the superposition of the emission of celestial sources, mostly AGN. Numerous space missions have measured the CXB spectrum, and few of them particularly surveyed the AGN population. As a result, the CXB is nearly (~93%) resolved into point-like AGN at soft X-rays (below 10 keV). A percentage decreases with increasing energy. Accurate measurement of the CXB spectrum and normalization is crucial to study the population of AGN, their obscuration, reflection, average spectra and ultimately the history of accretion in the Universe. The uncertainty on the CXB normalization (~15%) is one of the main sources of difficulty affecting the CXB modelling. We propose a detector to determine the CXB normalization with a per cent level accuracy. The detector consists of an array of tubes with collimated spectrometers and rotating obturators modulating the signals and allowing to precisely extract the CXB photons from the background. We present here a preliminary design of the detector which could be accommodated on various platforms (12U CubeSat, small satellite, space station). The 12U CubeSat option has been used to simulate the instrument performance with Geant4 taking into account the point sources and instrumental background to assess their respective count rates and the resulting accuracy on the CXB normalization. In two years, the CubeSat mission is able to measure it with an accuracy ~1% in the range of 10-100 keV ultimately limited by the quality of the calibration performed before the launch. This is a significant improvement compared to the current measurements.

The presence of a possible dipole in the angular distribution of the CXB could provide an absolute direction of the local speed of the Earth in the Universe compared to the AGN distribution [40-44]. CXBe will be the first instrument to have enough sensibility to probe the CXB dipole. Cosmological dipoles derived from the Cosmic Microwave Background, large-scale velocity flows, alignment of quasar optical polarization, anisotropy of expansion rate, the spatial dependence of the fine structure constant, large quasar groups do not match exactly and probe the first cosmological principle. There are also secondary sciences goals related to sources that could be pursued, for example, following transient Very-High-Energy sources like short Gamma-Ray Bursts (sGRBs) [9, 45-49], and measuring and monitoring luminous gamma-ray sources, e.g. the Crab which serves as a standard candle for space missions at high energies [50-51]. As the CXB is one of the major sources of background for space astronomical instruments, an accurate measurement will also help in general the cross-calibration of high-energy space missions.

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